

**CIBA FOUNDATION
COLLOQUIA ON AGEING**

Vol. 5. The Lifespan of Animals

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CIBA FOUNDATION COLLOQUIA ON AGEING

VOLUME 5

The Lifespan of Animals

Editors for the Ciba Foundation

G. E. W. WOLSTENHOLME, O.B.E., M.A., M.B., M.R.C.P.

and

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With 58 Illustrations
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of Aesculapius) holding a medical caduceus, and three regular hexagons for chemistry. Its domicile in London is indicated by the red sword of St. Paul and the British lion; the wyvern and the crozier, symbols associated with Basle, refer to the sponsoring firm located in this ancient Swiss town.

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PREFACE

EARLY in 1954 the Trustees of the Ciba Foundation designated funds over a period of five years for the encouragement of basic research relevant to the problems of Ageing. One feature of this special programme was to be the organization of small international conferences, on lines familiarly known at the Foundation in regard to other subjects in medical research, to assemble and consider such information as could be gathered in

from various sources. The Trustees now suspend the Foundation's special stimulation of work in this field. The Director believes that considerable attention has been drawn to the many large gaps in knowledge which must be filled before the postponement and amelioration of senescence can be realized. Research workers should now be left to their task, the size and importance

programme of the Foundation

The Director and his co Editor wish to place on record with these proceedings the indebtedness of the Foundation and themselves to Professor Danielli and Dr. Comfort for giving life

Longman & Co Ltd for minimizing, without skimping or harassment, the delay in publication in this difficult year.

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CONTENTS

	PAGE
Chairman's opening remarks J F DANIELLI	1
Actuarial aspects of human lifespans by B BENJAMIN	2
Discussion BENJAMIN BERG COMFORT DANIELLI GERKING GRÜNERBERG JALAVISTO ROCKSTEIN ROTBLAT SACHER SMITH	15
Parental age effects on man by EVA JALAVISTO	21
Discussion BENJAMIN BERG COMFORT DANIELLI HINTON JALAVISTO MÜHLBOCK ROCKSTEIN SACHER, SMITH	31
Studies on the longevity and mortality of English thorough bred horses by A COMFORT	35
Discussion COMFORT HARTWIG KERSHAW ROCKSTEIN SMITH	55
Lifespan of cattle and horses under various climatic con- ditions and the reasons for premature culling by W HARTWIG	57
Discussion BENJAMIN BOURLIERE, COMFORT DANIELLI HARTWIG KERSHAW MÜHLBOCK WOLSTENHOLME	70
Onset of disease and the longevity of rat and man by H S SIMMS B N BERG and D F DAVIES	72
Discussion BERG BOURLIERE COMFORT GERKING GRÜNE- BERG HOLT JALAVISTO MÜHLBOCK PERKS ROCKSTEIN ROTBLAT SACHER SMITH TANNER VERZAR, WIGGLESWORTH	79
Lifespans of mammalian and bird populations in nature by F BOURLIERE	90
Discussion BOURLIERE, COMFORT CHITTY DANIELLI KER- SLAW SACHER SCHEIDEGGER SMITH ROTBLAT	103
Arteriosclerosis in birds by S SCHEIDEGGER	106
Discussion BERG BOURLIERE, COMFORT DANIELLI HINTON KERSHAW JALAVISTO LINDOF NIGRELLI ROCKSTEIN SCHEIDEGGER, VERZAR	112

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	PAGE
Relation of lifespan to brain weight and body weight in mammals	
<i>by</i> G A SACHER	115
<i>Discussion</i> BERG, BOURLIÈRE, COMFORT, DANIELLI, HOLT, LINDOP, NIGRELLI, ROTBLAT, SACHER SMITH, VITZÁR, WIGGLESWORTH	133
A review of the lifespans and mortality rates of fish in nature and their relation to growth and other physiological characteristics	
<i>by</i> R J H BEVERTON and S J HOLT	142
<i>Discussion</i> BEVERTON, COMFORT, DANIELLI, GERKING HOLT, NIGRELLI, ROCKSTEIN, ROTBLAT	177
Physiological changes accompanying ageing in fishes	
<i>by</i> S D GERKING	181
<i>Discussion</i> COMFORT, DANIELLI, GERKING HOLT, NIGRELLI, ROCKSTEIN, ROTBLAT	208
Longevity of fishes in captivity with special reference to those kept in the New York Aquarium	
<i>by</i> R F NIGRELLI	212
<i>Discussion</i> BEVERTON, BOURLIÈRE, COMFORT, DANIELLI, GERKING, HOLT, NIGRELLI, ROCKSTEIN, SCHRIEDER	226
Factors influencing the lifespan of bees	
<i>by</i> ANNA MAURIZIO	231
<i>Discussion</i> BOURLIÈRE, COMFORT, HINTON, HOLT, KERSHAW, MAURIZIO, NIGRELLI, ROCKSTEIN, SACHER, WIGGLESWORTH	243
The biology of ageing in insects	
<i>by</i> M ROCKSTEIN	247
<i>Discussion</i> BERG, COMFORT, GERKING, JALAVISTO, KERSHAW, ROCKSTEIN, SACHER, SMITH, TANNER, WIGGLESWORTH	265
The rate of ageing in <i>Drosophila subobscura</i>	
<i>by</i> J MAYNARD SMITH	269
<i>Discussion</i> BERG, DANIELLI, GERKING, GRÜNEBERG, HINTON, KERSHAW, ROCKSTEIN, ROTBLAT, SACHER, SMITH, WIGGLESWORTH	281
Group Discussion	
BENJAMIN, CHITTY, COMFORT, GERKING, HOLT, MÜHLBOCK, PERKS, ROCKSTEIN, ROTBLAT, SACHER SMITH, TANNER, VITZÁR	286
Chairman's closing remarks	
J F DANIELLI	293
Appendix	
<i>Notes on some mathematical mortality models</i>	
<i>by</i> R E BEARD	302

of the division of causes of death into two kinds, those due to chance and those due to deterioration

It was soon evident that such a relatively simple law would not represent mortality experience throughout life and subsequent developments led to the proposal of more complex mathematical relationships between age and the force of mortality and even of different relationships over different parts of the age range Thiele (1871) for example proposed

$$\mu_x = a_1 e^{-bx} + a_2 e^{-b_1(x-c)} + a_3 e^{bx}$$

in which the last term is a Gompertz curve to represent old-age mortality, the first a decreasing Gompertz curve to represent the mortality in childhood, and the middle term a normal curve Perks (1932) introduced a new family of curves in the general form

$$\mu_x = \frac{A + Bc^x}{Kc^{-x} + 1 + Dc^x}$$

and rationalized this procedure with some interesting speculations on the theory of mortality He found an analogy between the "inability to withstand destruction" of Gompertz and the then current physical concept of entropy change—the measure of the time progression of a statistical group from organization to disorganization Perks also referred to the previous work of Karl Pearson who fitted overlapping curves not to the force of mortality but to the curve of deaths, the curves being intended to represent the mortality of old age, middle life, youth, childhood, and infancy, the causes of death being different in these different periods of life Perks pointed out that this search for homogeneity in the pattern of causes of death might lead to endless subdivision

$$\mu_x = \sum_{i=1}^n \mu_{xi} \quad \text{and} \quad d_x = \sum_{i=1}^n \mu_{xi} l_x dx$$

The continuous curve of $(\mu_x l_x)$ is called the curve of deaths.

ACTUARIAL ASPECTS OF HUMAN LIFESPANS

B BENJAMIN

General Register Office, London

ACTUARIES have always been profoundly interested in the variation in the incidence of mortality with age since many of their calculations of contingencies depend upon this variation. The study of this age variation in mortality has given rise to a number of hypothetical "laws" of mortality based on theories about the exertion on the human body of deleterious influences or about the wearing out of components of the body and the exhaustion of living resources. These theories date from Gompertz (1825) who argued on physiological grounds that the intensity of mortality (in his terms the average exhaustion of man's power to avoid death) gained equal proportions in equal intervals of age and Makeham (1867) who introduced a constant component as well as a logarithmically increasing component of the force* of mortality as a reflection

* It

$$\left(- \frac{l_{x+1}}{l_x} \right)$$

(4) q_x the chance of dying between exact age x and exact $x + 1$

$$\left(= \frac{d_x}{l_x} \right)$$

Note

$$p_x + q_x = 1$$

(5)

Later, in a discussion of another paper on fitting a mathematical law to l_x of the mortality table (Ogborn, 1953), Perks suggested that reference to the probability models of the biological field and the data of simple populations was the only way in which an advance would be made in the development of a satisfactory theory of a life table. It is a pity that this suggestion has not yet been exploited as, if linked with the idea of loss of biological organization, it seems to the present author to open up an important line of approach. But we are straying from the objective of this historical introduction.

In 1954 Phillips returned to consideration of the curve of deaths and hypothesized the existence of a basic curve of deaths 'to which all curves of deaths are, as it were, striving to attain'.

Clarke's division of deaths into "anticipated" and "senescent" has been further developed by Barnett (1955 and 1958) but applied to the force of mortality, not the curve of deaths. On the basis of cause of death grouping and the actual shape of the curve of observed age rates of mortality Barnett distinguished several different groups of anticipated deaths.

We may now return to Clarke's paper.

The earlier approach

The idea of a limiting curve of deaths, suggested by Clarke, is that every individual carried with him from birth a genetically endowed term of life beyond which it was impossible for him to survive, and that if we knew these terms for every member of the population we could form a frequency distribution similar to that of any other biometric quantity. This distribution would represent a limiting form of the curve of deaths. Clarke went further and supposed that this distribution would not shift as a whole toward later

of the curve of deaths into component curves and that it was questionable whether such subdivision could be theoretically validated. Nevertheless he agreed that one important case of sudden change of composition was the rapid transition between the period of physical growth and the adult period. "In the adult period we appear to be subject to a continually increasing disorganisation or 'inability to withstand destruction' while in childhood we appear on balance to gain organisation or 'ability to withstand destruction'."

While further work continued on the fitting of mathematical functions to the force of mortality, μ_x , attention was focused on the curve of deaths (i.e. of $\mu_x l_x$) as an alternative operand by a paper by Phillips (1935), though this was not yet to be taken up. Meanwhile, taking a closer look at the concept of deterioration, Rich (1940) evolved a theory of mortality based on an analogy between degrees of health and degrees of temperature. This gave rise to a "health frequency distribution" (a concept close to the present view of biological normality as a dispersion of characteristics within broadly separated limits), and changes of rating within this distribution could be regarded as forces of deterioration or of recuperation. A "natural law of mortality" emerged from which Makeham's and one of Perks's functions could be derived as special cases.

Clarke (1950) took up again the analysis of the curve of deaths. He argued that mortality improvements had not extended the natural lifespan but had only allowed more to achieve it. He distinguished between "anticipated" and "senescent" deaths, the ages at death in the latter group were measures of natural lifespans and had a frequency distribution like other animal characteristics. His paper formed the basis of the present work and his hypothesis will be referred to again presently.

Beard (1950) also paid attention to the curve of deaths, using the incomplete gamma function as the basic analytical function.

approximation to the curve of deaths (d_x is of course discontinuous while the "curve of deaths" is continuous. It has been assumed that $d_x \approx \mu_{x+1/2} l_{x+1/2}$). The curve has then been treated

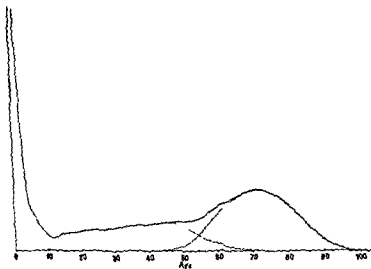


FIG. 1. Curve of deaths, English Life Table No. 1 1841 Males

— total deaths
 --- senescent deaths
 . . . anticipated deaths

side of this distribution has been drawn in (broken line in the figures) to exactly mirror the right hand side. It is thus assumed (unlike Clarke) that the biometric distribution of lifespans is symmetrical.

side of this distribution has been drawn in (broken line in the figures) to exactly mirror the right hand side. It is thus assumed (unlike Clarke) that the biometric distribution of lifespans is symmetrical. In effect it is assumed in Fig. 3 that no deaths before

ages, i.e. that the modal span of life was invariant, he rejected the possibility as "intangible speculation" outside the practical framework of his study, namely the relatively short term trend of mortality. Deaths were then divided into two categories, namely those which happened because the term of the lifespan had run out—senescent deaths—and all others, whether from accident or disease, which were in fact a cutting short of the lifespan—anticipated deaths. He first obtained, therefore, a limiting curve of deaths by constructing a table of mortality in which the q_x (probability of death between age x and age $x + 1$) column would consist of values (q_x^s) appropriate only to causes of death which could be regarded as senescent. The next stage was to predict the pace at which actual rates of mortality would in a given future period approach those of the limiting table. It is not necessary to discuss this aspect here.

Clarke originally intended to define 'senescent' deaths by choosing certain degenerative diseases (e.g. cerebral vascular lesions, myocardial diseases, angina pectoris, arteriosclerosis, other diseases of the circulatory system, bronchitis, nephritis), but he naturally found it difficult to select disease groups with sufficiently specific reference to degeneration. Ultimately therefore he arbitrarily assumed ratios of q_x^s/q_x rising from 0.05 at age 20 to 0.10 at age 40, 0.20 at age 50, 0.70 at age 70, 1.00 at ages 80 and above.

His limiting curve of deaths was not symmetrical. There was a sharp peak at age 80 with a tailing off rapidly on one side to age 100 or so and on the other side a rapid decline to about age 60 and then a much slower tailing off to age 20.

The present approach

The present author's approach has been even more arbitrary and pragmatic. In a particular life table the values of d_x (deaths between age x and $x + 1$) have been plotted for every value of x in the table (Figs 1-3), thus producing an

age 55 and all deaths after age 76 are senescent. It is hoped that this brash sweeping aside of the honest testimonies of millions of medical practitioners which are recorded in the vaults of Somerset House will not give offence. It is of course a moot point as to whether any death after age 76, even

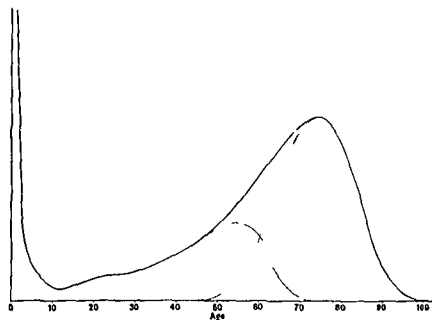


FIG 2 Curve of deaths English Life Table No 8 1910-1912 Males

— total deaths
 - - - - - senescent deaths
 anticipated deaths

allegedly due to some accident, is other than of senile origin, but some deaths before age 55 are of degenerative origin and at age 55 Clarke assumed that 20 per cent of them were "senescent". Whether this degeneration is senescent in the sense of the completion of a genetically endowed lifespan or whether it is the cutting short of the span by departure from optimum environmental conditions and behaviour is at least

arguable and it is proposed to adopt the latter hypothesis here.

The data used

The analysis already described was applied to three national life-tables (for both males and females, though Figs. 1-2 relate to males only):

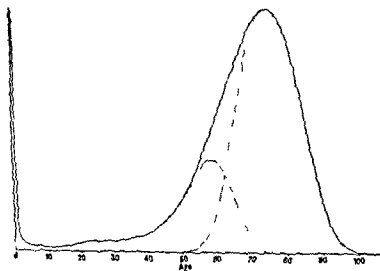


FIG. 3. Curve of deaths. *English Life-Table No. 11, 1930-1952. Males.*

— total deaths
 senescent deaths
 - - - - - anticipated deaths

English Life-Table No. 11, 1930-1952.

compiled by Dr.

It differs from

as both males and females start with a radix of 100,000 births, in that Farr to facilitate the product of a "persons" table chose radices of 51,274 male births and 49,726 female births (the proportions

of males and females in the births of that period) All the ordinates of Fig 1 should therefore be almost doubled to render it comparable with Figs 2 and 3, though the general shape is correct

English Life Table No 8 The first short period table prepared by an actuary, George King, for the Registrar General and based on the deaths of 1910-12

English Life Table No 11 Based on the deaths of 1950-52 and prepared by the Government Actuary

The results

The basic results of this analysis are

SENESCENT DEATHS

Period of deaths	Males			Females		
	Peak age	Standard deviation of distribution	Proportion of total deaths	Peak age	Standard deviation of distribution	Proportion of total deaths
1841	years 72 0	years 9 38	% 39 0	years 73 5	years 9 19	% 41 0
1910-12	" 1 5	8 70	51 5	76 0	8 51	53 3
1950-52	" 5 "	7 80	69 4	80 3	7 12	" 0 3

It is clear that from a practical point of view Clarke was right The main change in the hundred years or so has been the increase in the proportion of people attaining their allotted term of lifespan, from about 40 per cent to 70 per cent, while the shift in the peak has been a mere three or four years for men and seven years for women Judged by the standard deviation the spread of the distribution has narrowed a little but this is not a substantial change If—and it is a large question mark—this arbitrary distribution of "senescent" deaths can be used as an indicator of the natural

distribution of lifespan in humans then it appears possible that over and above the large increase in ability to attain the allotted span, the modal span itself is slowly increasing. Even in 1841 there had been a "break through" of the barrier of three score and ten. Women can now talk modestly of "four scores."

Comparison between men and women

If the proportion of all deaths which are senescent can be used as a measure of ability to survive the allotted term of life, then the improvement in the mortality of women as compared with that of men appears more as a greater shift in the optimum than as a greater improvement in attainment. The advantage of women over men (or conversely the disadvantage of men as compared with women) is thus a very general one and calls for intense examination.

Other aspects for examination

It would be possible to forecast mortality not only by examining the medical and environmental possibilities for the reduction of anticipated deaths as Clarke suggested but also by predicting the further change in the parameters shown in the table. It is tempting for example to suggest that the national life table in 1970-72 will show for men a modal span of almost 77 and an attainment of natural senescence by 78 per cent, but this kind of temptation will be pursued elsewhere.

Another possibility is that the "attainment" proportion (i.e. ratio of senescent deaths to all deaths) might be used as a mortality index for international comparison. This also is outside the present discussion.

The limitations of the life-table

The life table as normally computed is based on the rates of mortality experienced by the population of all ages as they

meniscus from minute to minute as urine collects in it (Hoy and Adolph, 1956). Quantitative collections can also be made without the cannula, at the urinary papilla or by bladder puncture; during rapid urine flows these collections give the same results as with the cannula (Heller, 1947; McCance and Wilkinson, 1947; Falk, 1955).

Water excess, administered by stomach tube, gives rise to very little diuresis at birth (Fig. 4). In the course of several

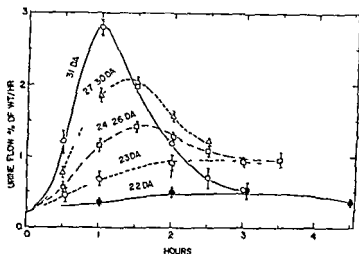


FIG. 4 Water diuresis at various ages in infant rats. Points show mean and standard error at end of each period of urine collection. DA = days after conception. From Falk (1955).

days the rat's response increases, until at about ten days after birth the response per unit of body weight is of adult size. The ages indicated on the graphs shown here are reckoned from conception instead of from birth, the average gestation time for rats being 21.3 days. Actually in human infants the maturation of the diuresis was found by Ames (1953) to be triggered by birth rather than by scheduled age, since prematures acquired the diuretic response about as soon after birth as postmatures did.

A familiar notion about the way in which water diuresis is excited is to suppose that the neurohypophysis withholds its

diuresis that is large and sudden even a few hours after birth. Likewise adrenaline or noradrenaline induces a full blown diuresis on the very day of birth. Evidently the capacity for excreting water at a high rate is present but its arousal depends on the particular form of stimulation. Consequently any discussion of structural inadequacies or functional immaturities seems beside the present main point, which is that the specific responding system of the newborn rat is not tuned to water excesses.

Hence we are privileged to see a physiological regulation increase in intensity in the growing individual. The regulation

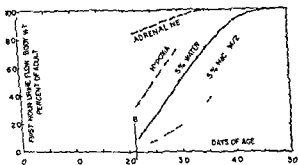


FIG. 7. Courses of development of four types of diuresis in rats. B = birth. From Hoy and Adolph (1956)

duly materializes whether the rat has ever experienced a water excess or not the elements necessary for it are there some of them long before this materialization. What guides the regulation's intensity and determines its point of adult fixation is unknown. The fixation is still subject to a small degree of adaptation resulting from previous exposure to water excesses (Adolph 1956).

The control of water intake on the other hand is much less understood than the control of water elimination. In early infancy rats like dogs (Adolph 1943 p. 267) refuse to drink water even after dehydration. According to Křeček, Křečeková and Dlouhá (1956) as late as 28 days after birth young

response is thus uncovered which is mediated through some other channel ordinarily masked by the known hormonal one

The intensity of diuresis is a function of the water excess at all ages (Fig 6), but the regression differs with age. Actually these data supply part of an equilibration diagram for infant rats, and by it one can watch the regulatory relations coming to maturity during early postnatal life. The unexcreted water has been located as excess in plasma and several other tissues. A possible theory of maturation is that some slowly developing process or structure limits the rate of water excretion.

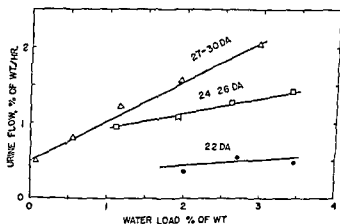


FIG 6 Water exchange in urine in relation to body water load at each of three different ages DA days after conception From Adolph (1957)

This theory is doubtful, since at every age still greater water excess arouses faster excretion. Rather, the response, expressed by the ratio between excretory rate and water load is small at birth and becomes greater as age increases.

However, in order to see whether diuresis is impossible at birth, we tested the capacity of the infant rat to respond to several other stimuli of diuresis. To concentrated salt solutions the diuretic response is practically nil at birth, and it matures even later than the water diuresis (Fig 7). Hypoxia arouses a primary diuresis that is small at birth and becomes greater a few days later, it also, however, arouses a secondary

both absolute (body size) and relative to body solids varies with the age of the rat (Fig 8) What controls the absolute content of water and of each solute? The answer to this question is not available Obviously all the items that enter the determination of growth and its correlatives participate in these controls This is a problem that has barely been visualized and one whose analysis may occupy many physiologists in the future

In general the ready corrections of water excesses and deficits result from specific response systems for diuresis and for water drinking The systems vary between infant and adult, not only quantitatively but possibly also in the mediators and effectors used Over a long lifetime the regulation depends also upon detectors of body size and proportions whose characteristics and locations have not been determined

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DISCUSSION

Shock We have obtained some data in our laboratory on the age differences in the antidiuretic response to pitressin Some of the results of these experiments are in accord with the concept that in many instances the senescent animal returns to a type of response and behavior that is seen during the neonatal period
 measured the
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rats drink more milk than water in recovering from dehydration. But in the same circumstance they drink more water than saline. Even newborn rats distinguish between milk and other fluids, at 17 postnatal days they distinguish between water and salt solutions. Such sensory discriminations are necessary before rats can link their intakes to specific deficiencies of bodily constituents. The actual tying of water drinking to water deficiency does not certainly occur until

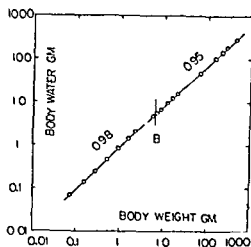


FIG. 8. Relation of log water content to log body weight in rats from foetus to adult. B = birth. Numbers represent exponents in parabolic equation relating the two quantities. Data of Hamilton and Dewar (1933) from Adolph (1957).

28 days after birth (Křeček, Křečková and Dlouhá, 1956). Already then the water intake of rats equals the water deficit imposed upon them (Adolph, Barker and Hoy, 1954, fig. 13); just as in the adults, the one hour intake closely matches the water deficit so long as the water deficit does not exceed six per cent of the body weight.

Once the immediate regulations of water content are fixed, the adult method of maintaining water balance is persistently at work. But it is well recognized that the water content,

both absolute (body size) and relative to body solids varies with the age of the rat (Fig 8) What controls the absolute content of water and of each solute? The answer to this question is not available Obviously all the items that enter the determination of growth and its correlatives participate in these controls This is a problem that has barely been visualized and one whose analysis may occupy many physiologists in the future

In general the ready corrections of water excesses and deficits result from specific response systems for diuresis and for water drinking The systems vary between infant and adult not only quantitatively but possibly also in the mediators and effectors used Over a long lifetime the regulation depends also upon detectors of body size and proportions whose characteristics and locations have not been determined

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DISCUSSION

Shock We have obtained some data on

as seen during
 measured the co
 flows Total urine
 subjects the nurse

the response of older animals with that of adults; they became comparable in quantitative terms only when the rats were 17-22 days old.

There is another point on which I should like to have your views, Prof. Adolph. We find that these responses of infant rats to vasopressin are

larger animals.

Black I am not sure of the exact age of the animals.

Adolph At the early ages these seem to have very little effect on water diuresis and water excretion.

Sayer I cannot speak about the water excretion.

Heller We have a few more experiments to do.

Adolph I should like to make a small protest against the term "immature".

immaturity For a phosphorus homeo functionally immature at birth even in the case of at least

the capacity to
adrenaline induced

diuresis? Did it increase the ratio of water to solutes in the urine, or did it increase the solute output?

Adolph Adrenaline diuresis in infant rats does involve more solute output than the water diuresis, but adrenaline diuresis is a water diuresis in that the urine is very dilute. I do not think you could blame all the adrenaline diuresis on the solute output itself.

With regard to immaturity and whether it takes experience for an animal to have a diuresis, we can point to the fact that adrenaline diuresis has no experience factor. We have tried to see whether we could get more water diuresis in the infant animal by subjecting it to water loads on successive days. There is a considerable variation in the amount of water excretion which is produced, and we are unable to say that there is any significant change due to previous experience with water. Our provisional conclusion is that there is no adaptation apparent in the animal subjected to repeated water loading.

CELLULAR ASPECTS OF THE ELECTROLYTES AND WATER IN BODY FLUIDS

HUGH DAVSON

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University College London*

THE water and electrolyte contents of a complex organism are almost entirely determined by the activities of the kidneys which operate primarily on the blood plasma and through that on the extracellular fluid of the organism. Casual fluctuations in the water and electrolyte contents of the organism are therefore usually the consequence of fluctuations in the composition of these two compartments of the body plasma and extracellular fluid. The electrolytes and water of the cells of the body are affected secondarily to these primary fluctuations in the composition of the extracellular fluid and plasma and for practical purposes at any rate the factors that can influence them primarily are usually ignored. Nevertheless since the cells occupy a considerable fraction of the total volume of the organism and since there must be some reciprocity between the electrolyte and water content of cells and extracellular fluid it is of some importance that we understand the physical and chemical factors that determine the electrolyte concentrations and volumes of the cells of the body.

The Gibbs Donnan Equilibrium The application of the Gibbs Donnan equilibrium to the problem of the water and electrolyte distribution between the plasma and extracellular fluid is familiar to all who have concerned themselves with the water balance of the organism. It will be recalled that the most important consequence of the Gibbs Donnan distribution of ions between the two fluids separated by the capillary membrane that is supposed to be impermeable to the protein molecules of plasma is that the osmolarity of the plasma is

significantly higher than that of the extracellular fluid. This is illustrated by Fig. 1, and it follows that an equilibrium will only be achieved when a counter-pressure is exerted on the plasma equal to the colloid osmotic pressure due to the plasma proteins. The amount of this difference of osmotic pressure is determined by the concentration and degree of dissociation of the proteins. Because of the high molecular weights of the plasma proteins, their concentration, expressed as moles per litre, is small and the difference of osmotic pressure that must be resisted, if the system is to remain stable, is correspondingly small, namely 25 mm. Hg. As a result, the organism is able to maintain a statistical equilibrium between plasma and extracellular fluid by virtue of the capillary pressure; at the

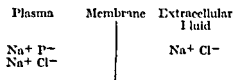


FIG. 1. The plasma-extracellular fluid system
(P=protein)

arterial end of the capillary the pressure is greater than this difference of osmotic pressure so that fluid flows into the extracellular compartment, at the venous end the reverse holds, and fluid is absorbed.

It is worth noting that by the term "impermeability" to a solute—here the plasma proteins—we do not necessarily mean an absolute barrier; this is an ideal case on which calculations are based, but practically it seems unlikely that a natural membrane is completely impermeable to any of the naturally occurring molecules in solution in the fluids, and it is sufficient for our purposes if by "impermeability" is meant that the rate of transport of this solute across the membrane is negligibly small compared with that of the other molecules that we are considering—in the particular case of plasma and extracellular fluid, the salts and water.

The cell membrane is a more selective barrier than the

capillary endothelium, and is capable of imposing restrictions on the movements of ions that are very much smaller than the protein ions, as a result, it is conceivable that much larger differences of osmotic pressure could be established, since these smaller ions may be present in vastly higher concentrations than those of proteins with their large molecular weights. Let us consider the erythrocyte, for simplicity we may choose the cat or dog erythrocyte which shows no accumulation of potassium. The distribution of ions is indicated roughly in Fig 2, the cell contains the protein haemoglobin which behaves as an anion, so that we may expect to be able to apply the Gibbs Donnan equilibrium to the diffusible ions. If the Na^+ , Cl^- and HCO_3^- ions could diffuse across the membrane, the position would be entirely

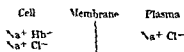


FIG 2 The cat erythrocyte
(Hb=haemoglobin)

analogous with that already considered, and the contents of the cell

plasma

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and we may since this difference of osmolarity must prevail so long as the cell contains a higher protein concentration than that in the outside medium. Cell membranes are not strong and would certainly not be able to resist the difference of osmotic pressure that would be developed, which in this case would be several times higher than in the case considered earlier owing to the very high concentration of protein in the red cell. We know that the cat erythrocyte is stable and we must ask how? Theoretically, stability could be achieved by making the membrane impermeable to all the ions.

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two main factors—the osmolarity of the plasma and the activity of this Na^+ extrusion mechanism. The passage of water across the cell membrane is very rapid, so that the cell responds to changes in osmolarity of the plasma by virtually instantaneous changes in its water content, in this way it may be said to respond passively to changes in the plasma, and its changes of water content and salt concentration may be said to be secondary to primary changes determined principally by the kidney. The operation of the second factor—the Na^+ extrusion mechanism—will influence the amount of material—salts and water—in the cell, and it would be by virtue of this mechanism that this type of cell could exert a primary influence on the water and electrolyte content of the organism. Thus, if the Na^+ extrusion mechanism operated more rapidly than the influx under the electrochemical gradient there would be a net loss of Na^+ and of anions, namely Cl^- and HCO_3^- , this would decrease the osmolarity of the cell and water would be lost to the plasma. Such a shrinkage of cells is easily demonstrable by allowing them to recover from the effects of putting the Na^+ extrusion mechanism out of action. Thus when the cells are cooled, the metabolic processes supplying energy can no longer work, Na^+ enters the cells accompanied by anions and they swell. When the cells are warmed the metabolic processes begin, and the extra Na^+ is excreted until the cells return to their normal volume. The effects of agents that increase the permeability of the cell membrane are of some interest, substances like alcohol or urethane in the appropriate concentration, can increase the permeability of the cell membrane to Na^+ and K^+ to such an extent that the Na^+ extrusion mechanism is unable to keep pace with the influx of this ion, thus, in spite of a normally functioning metabolism the cell may swell, on removing the agent it may return to its normal size.

The erythrocytes of most species contain K^+ as their principal cation so that the cell maintains large gradients of Na^+ and K^+ (Fig. 3). The condition for an osmotically stable system could be given by an impermeability of cations,

impermeable to cations such as Na^+ and K^+ . In this way the cell would be able to fulfil its function in the maintenance of the acid base balance of the body, *permitting the $\text{Cl}^- - \text{HCO}_3^-$ exchange that mediates the buffer action of haemoglobin in the cell*

membrane, so that any Donnan effect due to impermeable cations on one side of the membrane will be counterbalanced by an equal effect due to impermeable ions on the other side

It is easy to show that an osmotic equilibrium between the inside and outside of the cell is possible, in spite of the high concentration of indiffusible protein anions within the cell, thus the impermeability of the cell membrane to cations such as Na^+ confers on it a stability that would be lacking in the presence of a permeability to this ion, in other words, the colloid osmotic pressure of the cellular proteins can only operate in the presence of a permeability to both Na^+ and anions. It is now well known, however, that cell membranes do not show an absolute impermeability to such ions as Na^+ or K^+ , the use of isotopes has permitted the demonstration of an unequivocal exchange of these ions across the erythrocyte membrane. The exchanges are very slow compared with the exchanges of Cl^- and HCO_3^- , but they do occur so that we must expect a constant movement of NaCl and NaHCO_3 into the cell, associated with the migration of water unless some process prevents this. As is well known the process that does prevent it is an active transport of Na^+ ions out of the cell the membrane is permeable to Na^+ so that there is a continual drift of this ion into the cell because of the demands of the Gibbs Donnan distribution, but by some process not understood, *metabolic energy of the cell is employed in driving the salt out*. Practically, in consequence, the cell may be described as a cell impermeable to Na^+ and therefore in stable equilibrium with its environment. The total amounts of water and electrolytes within the cell will be determined by

excretion of Na^+ . The mechanism is not known; presumably the active transport processes are sensitive to the concentrations of Na^+ and K^+ , or more probably to the relative proportions of these ions, in the cell.

The erythrocyte is a highly specialized cell, and it would not be correct to assume that all cells of the body, or even the majority, are based on a similar physiological plan so far as the maintenance of salt and water content is concerned. The striated muscle fibre has been studied very thoroughly, and it may well be that this is far nearer to being a "typical cell", so that we may now consider its main features from the present point of view. The main point of difference between the muscle cell and the erythrocyte lies in the low contents of Cl^- and HCO_3^- , these anions being replaced by organic anions

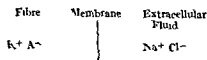


FIG. 4 The muscle fibre,
(A^- = indiffusible organic anions)

that apparently cannot diffuse across the plasma membrane, schematically the situation is as in Fig. 4 where A^- represents these indiffusible anions. The system would be osmotically stable were the membrane impermeable to Na^+ , i.e. the rest of the ions, K^+ , Cl^- , HCO_3^- , would distribute themselves across the membrane in such a way that equal osmotic activities would exist on both sides. Actually the cell membrane is permeable to Na^+ , and the reason why the Na^+ , K^+ and Cl^- ions do not redistribute themselves is because an active extrusion of Na^+ , as fast as it penetrates, maintains an effective impermeability to Na^+ . There is no need to postulate an active accumulation of K^+ in this case since, owing to the high concentration of impermeable anions in the cell, the extrusion of a Na^+ ion must be associated with the penetration of a K^+ ion in the interests of electrical neutrality. Once again, then, the cell may maintain equilibrium with its

as before, but once again studies with isotopes have shown that both Na^+ and K^+ can pass across the membrane and an active transport of Na^+ out of the cell and of K^+ into the cell must be postulated to account for the osmotic stability of the system

It was considered at one time that a mere extrusion of Na^+ would account for the osmotic stability and high concentration of K^+ in the cell, i.e. that the extrusion of Na^+ would demand a replacement by K^+ . It was pointed out however (Davson 1951) that this would lead simply to an excretion of NaCl and NaHCO_3 from the cell with a resultant shrinkage. Extrusion of Na^+ will only lead to accumulation of K^+ if exchange of K^+ for Na^+ is obligatory on the system in order to preserve electrical neutrality. If anions can accompany the excreted Na^+ then exchange for K^+ is not obligatory. In nerve and muscle where the concentration of non permeable anions in the cell is very high such a sodium excreting mechanism would cause accumulation of K^+ .

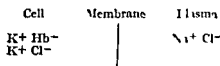


FIG. 3 The human erythrocyte
(Hb=haemoglobin)

Once again, the water content of such a system will be determined by the osmolarity of the plasma and the activity of the metabolic ionic pumps, thus over activity of the Na^+ excreting mechanism would lead to a shrinkage over activity of the K^+ accumulating mechanism would lead to a swelling. It is interesting that the two processes show some degree of linkage, in that Harris (1951) has shown that accumulation of the one ion is associated with a nearly equivalent excretion of the other. The linkage is not complete, however, since on cooling erythrocytes swell as a result of gaining more Na^+ than they lose K^+ , when they are re warmed the extra Na^+ is excreted and they return to their original volume. The fact that the cell maintains its characteristic water content and proportions of Na^+ to K^+ within fairly narrow limits indicates that there is some homeostatic mechanism controlling the rates of accumulation of K^+ and

excretion of Na^+ . The mechanism is not known, presumably the active transport processes are sensitive to the concentrations of Na^+ and K^+ , or more probably to the relative proportions of these ions, in the cell.

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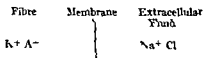


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impermeable anions in the cell, the extrusion of a Na^+ ion must be associated with the penetration of a K^+ ion in the interests of electrical neutrality. Once again then the cell may maintain equilibrium with its

environment, provided that an ion excreting mechanism is active. Loss of this, by cooling the tissue or by metabolic poisons, causes a loss of K^+ and a gain of Na^+ , Cl^- and HCO_3^- , the net effect being an increase in osmolarity with a consequent swelling of the cells. Re-warming of the tissue may cause a reversal of these changes (see, for example, Steinbach, 1954).

Thus, in all of the cell types that we have considered the system can be treated, theoretically at least, as a system that maintains an osmotic equilibrium between the interior and external fluids by virtue of an 'effective impermeability' to one or more ionic types, if the membrane were truly impermeable to the ions in question, the osmotic equilibrium would be independent of metabolic processes and could be described as a true equilibrium, in practice, the effective impermeability is the result of a continuous process of active transport. For the purposes of mathematical description this is equivalent to an impermeability, at any rate under normal conditions, under abnormal conditions, on the other hand, the precariousness or instability of the equilibrium is shown by the cellular oedema that follows either the failure of the ion excreting mechanism or such a large increase in the permeability of the membrane that the mechanism can no longer keep pace with the influx of Na^+ .

If these considerations are correct, we may expect to find that by adding up the total osmolarities inside and outside the cell the two totals should be equal within the limits of experimental error. Probably the muscle fibre has been studied most carefully from this aspect and it would seem from Conway's (1957) figures (Table I) that osmotic equilibrium does exist between the cell and its environment. The same is probably true of the erythrocyte and the nerve fibre, but it must be remembered that the analytical techniques for all the constituents of the cell are not so accurate that a difference of one or two per cent would be ascertained. Within this limit, then, it seems quite safe to affirm that these cells are in osmotic equilibrium with their environment.

Within recent years the possibility that mammalian cells

are not in osmotic equilibrium with their extracellular fluid has been seriously maintained, and an "osmotic pump", driving water continuously out of the cell, has been postulated. The experimental basis for this claim rests on the observation that mammalian tissue slices, in particular those of liver and kidney, swell when placed in "isotonic" solutions of sodium chloride, Tyrode or Krebs (Sperry and

Table I
COMPOSITION OF FROG MUSCLE AND PLASMA EXPRESSED AS M MOLE PER kg
H₂O (after Conway, 1957)

	Fibre Concentration	Plasma Concentration
K	124	2.25
Na	10.4 (3.6)*	109
Ca	4.0	2.1
Mg	14.0	1.25
Cl	1.5	77.5
HCO ₃	12.4	26.6
Phosphate	7.3	3.3
Sulphate	0.4	2.0
Phosphocreatine	35.2	—
Carnosine	14.7	—
NH ₃ -acids	8.8	7.2
Creatine	7.4	2.2
Lactate	3.9	3.5
Adenosine triphosphate	1.0	—
Hexose monophosphate	2.5	—
Glucose	—	4.1
Protein	0.6	2.2
Urea	2.0	2.1
Total	<u>248.2</u>	<u>245.3</u>

* Figure in brackets for sodium represents, according to Conway, the true intracellular concentration.

Brand, 1939; Opie, 1949), either at room temperature or at 0°. Robinson (1952) observed that the swelling could be prevented or reversed by maintaining the tissue at 37°, he found also that the swelling occurred in the presence of cyanide at this temperature. Since swelling was prevented by using strongly hypertonic solutions—0.55–0.60 M—he concluded that the cells were iso osmotic with these. It will be quite clear from what has been said earlier that these facts may be explained just as easily on the assumption that the electrolyte

excreting system fails at low temperature or in the presence of cyanide. Thus soaking a muscle at 0° certainly leads to swelling but this is completely accounted for by the gain of Na^+ and Cl^- , warming the muscle causes an excretion of these ions and it returns to its original volume. The same argument will apply to other tissues and conclusive proof that this is the principal explanation for the changes taking place on cooling was provided by the elegant experiments of Deyrup (1953) who showed that if the tissues were bathed in iso osmotic sucrose (0.3 M) they failed to swell. If the swelling in Ringer solution had been due to a failure of a water excreting mechanism substitution of salt for sucrose should have had no effect, whereas if the swelling had been due primarily to a penetration of NaCl substitution of a non penetrating substance like sucrose would have prevented it. It seems safe to conclude then that very large differences of osmolarity between cell contents and their environment such as those postulated by Opie (1949) and Robinson (1952) do not occur. The detection of smaller differences that would demand a water pump continuously excreting water from the cell to maintain an osmotic steady state between cells and their environment, must rely on very precise measurements of osmolarity.

The depression of freezing point has been employed by a number of workers with a view mainly to testing the claim that mammalian tissues were hypertonic to plasma (Conway and McCormack 1953, Opie 1954, Brodsky *et al.* 1953, 1956, Conway, Geoghegan and McCormack 1955, Itoh and Schwartz 1956) but as Conway's studies indicate the interpretation of the results is not easy since an excised tissue when ground up at 0° , undergoes autolytic changes—in particular the breakdown of adenosine triphosphate to inosinic acid, ammonia and phosphate—that lead to a considerable increase in osmolarity. It would seem from Conway's studies that within the limits of accuracy of the cryoscopic method—probably a few per cent—the tissue cells examined (liver, kidney and muscle)—are iso osmotic with their environment.

This does not mean, however, that the maintenance of differences of osmotic pressure between cells and their environment by the excretion of water does not occur, it is well known that such fluids as urine and saliva have osmolarities that are vastly different from that of the plasma, and the elaboration of these fluids is best described by invoking an active transport of water—i.e. the functioning of a "water

Table II

CONCENTRATIONS OF IONS (M MOLE/KG H_2O) IN PLASMA, AQUEOUS HUMOUR AND CEREBROSPINAL FLUID OF THE RABBIT

<i>Plasma</i>				<i>Aqueous Humour</i>			
Na	151.5	Cl	108	Na	143.5	Cl	109.5
K	5.5	HCO ₃	27.4	K	5.5	HCO ₃	33.6
Ca	2.6	Lactate	7.9	Ca	2.3	Lactate	6.00
Mg	1.0	Phosphate	1.8	Mg	0.80	Phosphate	1.00
						Ascorbate	1.00
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Total	160.6	Total	140.1	Total	152.1	Total	151.1
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Cations and Anions 305.7				Cations and Anions 303.3			

<i>Cerebrospinal Fluid</i>			
Na	151	Cl	129
K	3.5	HCO ₃	31.4
Ca	1.3	Lactate	2.6
Mg	0.8	Phosphate	0.5
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Total	156.6	Total	163.5
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Cations and Anions 320.1

pump' The cerebrospinal fluid would appear to represent another example of a non iso-osmotic fluid, and since it is in such close relationship with the nervous tissue of the brain and spinal cord, this lack of iso osmolarity is of special interest, suggesting as it does that these tissues, too, are not in osmotic equilibrium with the blood. The results of a detailed analysis of the ionic concentrations in plasma and cerebrospinal fluid are shown in Table II, included are values for a similar

excreting system fails at low temperature or in the presence of cyanide. Thus, soaking a muscle at 0° certainly leads to swelling, but this is completely accounted for by the gain of Na^+ and Cl^- ; warming the muscle causes an excretion of these ions and it returns to its original volume. The same argument will apply to other tissues, and conclusive proof that this is the principal explanation for the changes taking place on cooling was provided by the elegant experiments of Deyrup (1953) who showed that if the tissues were bathed in iso-osmotic sucrose (0.3 M) they failed to swell. If the swelling in Ringer solution had been due to a failure of a water-excreting mechanism, substitution of salt for sucrose should have had no effect, whereas if the swelling had been due primarily to a penetration of NaCl substitution of a non-penetrating substance like sucrose would have prevented it. It seems safe to conclude, then, that very large differences of osmolarity between cell contents and their environment, such as those postulated by Opre (1949) and Robinson (1952), do not occur. The detection of smaller differences, that would demand a water pump continuously excreting water from the cell to maintain an osmotic steady state between cell and their environment, must rely on very precise measurements of osmolarity.

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Total	160.6	Total	145.1	Total	152.1	Total	151.1
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Cations and Anions 303.3

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Cations and Anions 320.1

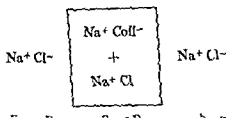
pump" The cerebrospinal fluid would appear to represent another example of a non iso-osmotic fluid, and since it is in such close relationship with the nervous tissue of the brain and spinal cord, this lack of iso osmolarity is of special interest, suggesting as it does that these tissues, too, are not in osmotic equilibrium with the blood. The results of a detailed analysis of the ionic concentrations in plasma and cerebrospinal fluid are shown in Table II, included are values for a similar

type of fluid, the aqueous humour—similar because both are specialized tissue fluids filling cavities and being virtually free from protein. By summing the cations and anions it becomes clear that the cerebrospinal fluid has a higher concentration than the plasma or the aqueous humour, allowance must be made for the lower concentrations of glucose and urea in the cerebrospinal fluid, a difference amounting to some 5 m mole, thus the cerebrospinal fluid is hyperosmotic by some 9 m mole. The amount is small—some 3 per cent—nevertheless it represents a difference of osmotic pressure of some 160 mm Hg, and it is presumably because the fluid is able to drain away easily from its cavities that this pressure does not develop, i.e. the difference in osmolarity is reflected in a continuous influx of water from the blood rather than in the development of a pressure, such as would happen were the system completely closed. However, the really significant point to be made in this connexion is that the cerebrospinal fluid lies in such close relationship with the brain and cord that it seems most unlikely, having regard to the rapidity with which water may exchange between the two, that a difference of osmolarity could be maintained. That is, if the cerebrospinal fluid is, indeed, hypertonic to plasma, then so must the tissue of the brain and cord be. If this is true, then we may postulate one of two things: either a water pump that drives water out of the nerve cells into the extracellular fluid where it passes back into the blood, or alternatively the elaboration, by the capillaries of the nervous tissue, of a hyperosmotic extracellular fluid. The capillaries in this region of the body are certainly different from those in the rest of the body and are responsible, presumably, for the so called "blood brain barrier", to attribute secretory activity to their endothelium is by no means an unreasonable proposition. The important point to be made here is that the difference of osmolarity is small and thus requires highly accurate analysis for its demonstration. Why the cerebrospinal fluid and nervous tissue should have this higher osmolarity is not clear, according to Flexner (1938),

the high concentration of chloride in the cerebrospinal fluid,

in fact. It may be that the positive pressure of the spinal fluid depends for its maintenance on a difference of osmotic pressure between it and the blood.

The factors determining the water and electrolyte contents of connective tissue are probably simple, although they have not been studied in great detail. If a piece of collagen, or collagen plus mucoid, is placed in a saline medium, equivalent to extracellular fluid, we may expect a Gibbs Donnan equilibrium to be established between this and the medium by



phase

virtue of the acidic nature of the protein and mucoid. The situation might therefore be as in Fig 5, i.e. essentially similar to that obtaining with plasma separated by a membrane from extracellular fluid. There is no membrane separating the two however and separation is maintained because of a phase difference the collagen mucoid system being a gel, the extracellular fluid a liquid. Chemical analysis of connective tissue shows that there is indeed, a Gibbs Donnan distribution of ions between it and plasma and therefore, presumably between it and extracellular fluid, the concentration of chloride being less and that of sodium greater, in the connective tissue. There is in consequence, a tendency for water to pass into the connective tissue phase, the salts

continuously redistributing themselves so that the osmotic pressure of this phase is greater than that of extracellular fluid and of blood. The extent to which the system will take up water will depend on the counter pressure that can be exerted or, failing that, what is really equivalent, the mechanical rigidity of the system that will oppose distention. Presumably in such tissues as tendon and skin the structural rigidity of the system prevents an indefinite uptake of water, and the system is stabilized with a water content of about 75 per cent. In the cornea of the eye, however, the situation

Table III

COMPARISON OF EYES MAINTAINED AT NORMAL AND LOW CORNEAL TEMPERATURES
(DAYSON, 1935)

Expt no	Temp (°)	Time (hr)	Water Content	
			(g /100 g tissue)	(g /g solid)
1	7	15	82.8	4.8
	31	—	77.2	3.4
2	7	15	82.8	4.8
	31	—	77.0	3.35
3	7	17	82.1	4.65
	31	—	78.2	3.6
4	7	7	78.5	3.65
	31	—	77.8	3.5

is different, it consists, essentially, of a number of laminae of collagen plus mucoid, sandwiched between two cellular layers, the epithelium and endothelium. If the eye is excised and stored in the cold, say at 4°, the cornea increases in water content, due to absorption of aqueous humour. If instead of being kept at 4° the eye is maintained at about 31°—the normal temperature of the cornea—the tissue retains its normal water content (Table III). It would seem, then, that metabolic activity is preventing the collagen plus mucoid from absorbing water and salts from the aqueous humour, and this may be proved by first allowing the cornea to swell at the

low temperature and then transferring the eye to a chamber maintained at the higher temperature. In this case the absorbed water and salts are excreted back and the cornea reacquires its normal hydration (Table IV). The secretory activity that usually maintains the cornea in its normal state of hydration—about 75 per cent water—may be due to both the endothelium and epithelium but whether it is due to an active excretion of salt e.g. sodium or of water remains to be proved. The extraordinary tendency of the cornea to take up water by contrast with tendon or sclera, is presumably

Table IV
THE EFFECT OF SUBSEQUENT WARMING ON EYES MAINTAINED FOR 15-18 HOURS AT 7°
(Dawson 1935)
Column A gives the water content after the period at 7° column B the water content after a further period of 6-8 hours at 31°

Expt no	Water content (g/g solid)		Change (%)
	(A)	(B)	
1	4.35	3.3	24
2	5.1	3.0	41
3	4.45	3.7	17
4	4.65	3.9	16

related to the large quantity of mucoid present as a coating over the individual collagen fibrils (Schwarz 1933) and it seems likely that changes in hydration are really the consequence of changes in hydration of this colloid the collagen fibrils being pushed apart by the swelling. The Gibbs Donnan swelling of the collagen mucoid system of skin and subcutaneous tissues may well be a factor in determining the water content and the turgescence of the tissues. Thus it would seem from McMaster's (1946) studies that the extracellular fluid may in normal circumstances be something of an abstraction the space between cells and collagen fibrils being occupied by a mucoid gel only when excessive amounts of fluid are filtered from the plasma or under experimental

conditions of injection of fluid into the tissue, is it possible to speak of free fluid in the extracellular spaces. The nature of the collagen and mucoid in these tissues may therefore exert some effect on the water content of the tissues. In general it would seem that acute changes in this tissue extracellular water are the result of changed factors of capillary filtration and reabsorption, but it may well be that the long term steady state level is influenced by the amount of mucoid in the tissue. This presumably exerts its Gibbs Donnan difference of osmotic pressure, drawing fluid to it, the tendency is opposed by the structural rigidity of the tissue, so that a steady state is established in contrast to the corner where the rigidity of the system is inadequate to permit a steady state a continuous secretory activity being necessary, and made possible by the presence of cellular membranes lining the tissue.

The possible ways in which the water compartments of the body may be altered with age become evident from this general review, thus the activity of the ion transporting mechanisms of the cells tends to oppose a normal tendency to cell oedema, with the result that a steady state is maintained with the cells having a characteristic ionic make up and percentage of water. A decrease in the metabolic activity of the cells may be expected to result in the penetration of salt and water into the cells, hyperactivity, on the other hand may cause a shrinkage of the cells but the extent of this will be limited by the demands of electrical neutrality. excessive excretion of the Na^+ ion must be associated with excretion of some anion or with accumulation of K^+ in the latter event there will be no change in osmolarity, whilst the former process is limited by the availability of diffusible anions. It seems unlikely that a cellular dehydration could result from hyperactivity of this sort, and it seems more likely that dehydration of cells might be due to a loss of the indiffusible anions collectively indicated as A^- in Fig. 4 but actually consisting of proteins, organic phosphates etc. If these were replaced by such diffusible anions as Cl^- and HCO_3^- , then the process of

extrusion of Na^+ would lead to an elimination of these ions and it could well be that a new steady state would be established at a lower level of internal K^+ and Na^+ concentrations. Unfortunately, practically nothing is known of the factors that control the normal activity of the salt excreting system of the cell.

The large differences in the amount of extracellular water that take place with age may be to some extent, associated with differences in the amount of water per cell of the organism thus other things being equal a decrease in cellular water is reflected in a rise in the extracellular water, expressed as a percentage. To prove this however, it would be necessary to measure not so much the percentage water in the cells as the amount of water per cell and this might be attempted by relating the water to the deoxyribonucleic acid content of the tissue. It seems more likely however, that long term fluctuations in the fractions of intra and extracellular water, especially those taking place during development will be determined by changes in the

of tissue rather

achieved by

cells (b) expansion or contraction of the extracellular space by changes in the quantity of connective tissue and in the ability of this to hold fluid

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representative sample of what is going on in the organism. Is this a fair assumption? A second point is that most of the work has been done on kidney slices. Are kidney slices representative of the whole organism, or only of the kidney tissue?

Fejfar Cort and Kleinzeller find that the amount of potassium and sodium

Fejfar Roguski in Poland claims that one can judge general cellular metabolism from the red cell. The red cell is a good indicator of metabolic activity. The red cell is a good indicator of metabolic activity. The red cell is a good indicator of metabolic activity.

Dawson difference

that the only cells in significant amounts and that only sodium does this, so we judge the extracellular fluid by the chloride present

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DISCUSSION

Talbot I was most interested, Dr. Dayson, in your comments about the cellular oedema that occurs in 'sick' cells. It has been shown that animals deprived of potassium, and thereby subjected to a combination of cellular potassium insufficiency and cellular sodium intoxication, show a tendency to cellular oedema. We therefore wondered whether loss of potassium from the cell was a factor which might interfere with its sodium and water pump mechanisms.

ment of more of these ions and to a condition in which there is a high potassium concentration inside, and low sodium and chloride. When we allow the system to cool or give it poison, then we find that sodium comes

we do not really know
ther
um.

Dayson So you propose a condition where there is a sodium as well as a potassium deficiency?

Talbot You could have simple deprivation with loss of cellular potassium. We are not sure whether it is a simple deprivation or whether it is a combination of potassium deficiency and sodium intoxication.

Dayson It is really a matter of thinking these things out. We are not sure whether it is a simple deprivation or whether it is a combination of potassium deficiency and sodium intoxication.

when we analyse a muscle biopsy specimen, that we find a high concentration of potassium and a low concentration of sodium.

Maybe someone can furnish data which will be more convincing on whether the electrolyte transfers are equally rapid and reproducible.

Darson I think the electrolyte transfer is very likely to be much slower and to hold up the whole process. The water transfer is very rapid in every cell so I would say that what happens first is the movement of the electrolyte and the movement of water would not require much time. The evidence I am citing is largely based on work from Prof. Conway's laboratory.

Datson That would be a most dangerous conclusion to draw. If your chloride space altered under experimental conditions, it could very well be due to penetration of chloride into the cells.

Wallace We have been working with tissues for some time from the standpoint of hydrogen ion gradients between cells and extracellular

analytical values for whole tissues. They point out that the interior of the cell is not homogeneous. Potassium and sodium do not appear to be evenly distributed and the hydrogen ion concentration seems to vary from locus to locus. I am certainly not ready to give up the study of ions and their distribution in tissues, but I think one must always bear in mind that membrane equilibria can only tell a part of the story. The concept of the cell, particularly the muscle cell, as an "empty bag" cannot be completely accepted.

Datson In general I am in favour of your iconoclastic approach but you are basing most of your argument on the findings of the electron microscopists and they are by no means above criticism themselves. They are working on fixed tissue and talk about their endoplasmic reticulum. It certainly appears as a most complicated system of canals, but one wonders how elementary physicochemical complexities?

brane with certain permeability characteristics. The electron microscopists show us the membrane which does exist but then they find little

have obviously got to be suspicious of treating things too simply—there you are absolutely right. On the other hand I am not willing to stop applying elementary physical chemistry to problems of salt transfer just because of these complexities.

Adolph I should like to add something to the point about swelling and shrinking with the accompanying transfers of electrolytes. When tissue slices, not only kidney slices but also liver slices and two tissues which we did not have to slice—the diaphragm and auricle—are transferred from

vinced that the electrolyte transfers are necessary for this swelling and shrinking. We have no method of measuring the speed of the electrolyte transfers, but we have a method of measuring that of the water transfers

Before discussing the subject in more detail it may be helpful to recall some of the factors which regulate the water content of the body

Regulation of water

Two mechanisms, closely linked, normally guard against water depletion. One regulates the intake of water through the sensation of thirst, the other the output of water through the secretion of antidiuretic hormone. There are at least two ways in which each may be invoked: the first, a rise in the tonicity; the second, less well known, a fall in the volume of the body fluids (Smith, 1957; Strauss, 1957).

A rise in the sodium content of the extracellular fluid (ECF) is well known to produce thirst and to stimulate the release of antidiuretic hormone (ADH). The *effective stimulus* is not simply the rise in ECF tonicity: if the ECF tonicity is raised with a substance like urea, which diffuses freely across the cell membrane and raises the tonicity of both extracellular and cellular fluid equally, this does not stimulate thirst and antidiuresis to the same extent (Gilman, 1937). When, however, the extracellular tonicity is raised by a substance which does not diffuse into the cells, water leaves the cells until the tonicity of extracellular fluid and cells are again equal. The cells shrink. It is assumed that certain cells in the hypothalamus stimulate the sensation of thirst.

As for ADH, there is much evidence that there are localized receptors of this kind (Jewell and Verney, 1957; Verney, 1957). Recently Andersson (1957) has also provided additional evidence for a thirst centre. He found that when he stimulated a certain area of the hypothalamus in goats, they drank water as long as the stimulus went on, even to the point of haemolysing their own red cells. With destructive lesions in the same region, the goats would not drink water when they obviously needed it. The thirst centre and the receptors of the ADH mechanism are very close together, but probably distinct.

HYPERNATRAEMIA AND HYPONATRAEMIA WITH SPECIAL REFERENCE TO CEREBRAL DISTURBANCES

PAUL FOURMAN and PATRICIA M. LEESON

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Introduction

AN abnormal concentration of sodium in the extracellular fluid often presents a puzzling problem for the clinician. As is well known, a change in the total amount of the sodium or of the water in the body can explain many instances—water deficiency or sodium excess producing hypernatraemia, water excess or sodium deficiency producing hyponatraemia. But many cases appear to require more than a simple account of gains and losses to explain them. Is this because a simple explanation, such as a change in the amount of water in the body, has been overlooked, or must one in such cases invoke some new mechanism, possibly under the control of the nervous system?

There have been a number of reports of 'cerebral' hypernatraemia and hyponatraemia (Knowles, 1956, Edelman, 1956). With regard to hypernatraemia it seems likely that some of the contradictions in the present views (Welt *et al*, 1952, Higgins *et al*, 1954) might have been avoided, for in hardly any of the patients reported could a frank water deficiency confidently be excluded from the information supplied. This question is discussed in the first section. The subject of hyponatraemia seems much more difficult but if sodium deficiency is excluded, many of the remaining cases can be accounted for by an abnormal retention of water diluting the body fluids. In the second section we present some new data on the problem, derived from a study of two patients.

nexion it may be recalled that two of Allott's patients had had an alimentary haemorrhage

It is partly through neglect of this phenomenon that some authors have been led to place cases of hypernatraemia with a low urinary sodium in a separate group

Symptoms of water deficiency There are several reasons why authors describing neurogenic or cerebral hypernatraemia may have overlooked a water deficiency. Though they often state that there is no clinical evidence of dehydration in their patients (e.g. Cooper and Crevier, 1952), this does not in fact mean very much. The word *dehydration* is used for two clinical states: one of water deficiency alone, and the other of salt deficiency which generally also entails a loss of water. This usage implies that these deficiencies produce a similar clinical picture, though it was made clear long ago that this is not so (Kerpel Fronius 1935; Nadal, Pedersen and Maddock, 1941). Water deficiency is not clinically obvious unless it is extreme, because the deficit is distributed throughout the body water. In salt deficiency, on the other hand, the extra-cellular fluid, though but a third of the total in volume, bears the whole of the deficit, it is patients with the latter who have the haggard look, the sunken eyes, the small pulse and low blood pressure of dehydration. Patients with simple water deficiency are ill, but there are no specific signs of the deficiency: the tongue may even be moist, and it is not obvious it is water they lack. If in addition, as a result of a craniotomy, their faces are oedematous, it may even be mistakenly assumed that they have accumulated water in excess. The diagnostic difficulties are increased because, particularly in older patients, some of the most striking symptoms of water deficiency are cerebral rather than vascular: for instance, drowsiness and confusion and disturbances of behaviour, which can mimic a lesion of the frontal lobes. These symptoms make it more difficult to give water, but they can be completely reversed with water.

Losses of water Abnormally large losses of water may go unrecognized. Extrarenal losses may be larger than is

The position of these centres in the nervous system suggests that their control involves more than a response to changes in tonicity, and some purely nervous stimuli such as pain and emotion may initiate, or inhibit, thirst or antidiuresis

A fall in the volume of the ECF can stimulate thirst and antidiuresis, presumably through nervous pathways (see Rosenbaum, 1957, Strauss, 1957) Smith (1957) has discussed at length where the receptors for the stimulus to antidiuresis might be some of them may be in the left auricle of the heart (Henry and Pearce, 1956)

Hypernatraemia

Water deficiency

Normally, thirst and antidiuresis are stimulated by a very small increase in extracellular tonicity, less than two per cent (Wolf, 1950, Verney, 1957) A concentration of sodium ($[Na]$) in the plasma exceeding 150 m equiv/l may certainly be regarded as abnormal In a study of water deficiency produced experimentally in dogs values of 160, and in one animal that died a value of 186 m equiv/l, were found (Elkinton and Taffel, 1942), in a man made water deficient by Black, McCance and Young (1944) the $[Na]$ rose to 160 m equiv/l In a patient from Texas reported by Gordon and Goldner (1957) a value as high as 192 m equiv/l was reported He recovered

The "dehydration reaction" The hypernatraemia of water deficiency is not simply the result of the blood becoming more concentrated, for in spite of the high blood level of sodium there may be very little sodium in the urine, it is retained in the body

Allott (1939), who first drew attention to the problem of hypernatraemia, found the urinary $[Na]$ ranged from 2.5 to 9 m equiv/l in four of his patients It now seems most likely these low concentrations of sodium were a result of the "dehydration reaction" first described by Peters (1948, 1952) The mechanism of this reaction is not clear, though it appears to be a renal response to a fall in blood volume, in this con

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generally assumed, and a good urinary output does not necessarily mean there is no deficit of water, for it may represent failure of conservation. In the unconscious or helpless patient the intake depends on the physician's instructions and the nurses' care. If the intake is less than the combined losses from the skin, the lungs and the bowels, there must be a deficit of water in the body and the plasma $[Na]$ will eventually rise.

Some cerebral lesions are associated with a high fever, or with excessive sweating or with an abnormally rapid respiration. With any of these the insensible losses of water may increase from the normal value of some 800 ml. They have rarely been measured, but in one patient they were thought to be as much as five litres a day (Gordon and Goldner, 1957).

One expects the volume of urine to be small in water deficiency, and its concentration high. But there are three ways in which untoward renal losses of water may contribute to water deficiency: diabetes insipidus from a failure of the pituitary hypothalamic mechanism, defective renal function, and osmotic diuresis. Neither the first nor the second has always been excluded in cases reported as cerebral hypernatraemia. Diabetes insipidus possibly explains cases 1 and 3 of Cooper and Crevier (1952) and one case of Natelson and Alexander (1955). The force of this explanation is emphasized by a patient reported by Peters (1948): a young woman whose serum $[Na]$ rose from 140 to 171 m equiv/l in 24 hours following an operation for craniopharyngioma which was complicated by diabetes insipidus. In an incontinent patient a low concentration of the urine may be the only clue to diabetes insipidus and the effect of pitressin should be tried in all patients with hypernatraemia in whom this possibility exists.

The excretion of a large amount of solutes produces an osmotic diuresis (McCance, 1945; Hervey, McCance and Fayler 1946; Rapoport *et al*, 1949). This happens in spite of a water deficiency (McCance, Young and Black 1944) and may even be the cause of it.

Urea, sodium and chloride are the main osmotically active constituents of the urine. The excretion of urea may be

increased by an abnormal breakdown of body protein or by excessive protein in the diet. One hundred grams of protein contain 16 g. of nitrogen, excreted as 34 g. or 570 m-osm. of urea. Ten grams of sodium chloride provide 340 m-osm. It is not unusual for unconscious patients to receive these amounts in their feeds; and their endogenous production of urea may already be very large (Cooper *et al.*, 1951). The hypernatraemic patient of Natelson and Alexander (1955) presumably had an osmotic diuresis when he was made worse with "non-saline fluids", because these consisted partly of protein hydrolysate equivalent to 100 g. of protein. In certain neurological disturbances (Astrup, Gotzche and Neukirch, 1954; Whedon and Shorr, 1957) and in water deficiency itself (Black, McCance and Young, 1944) the breakdown of body protein may be greatly accelerated.

To detect a water deficit, the minimum data required are the estimated intake and output of water and solutes, and the volume and concentration of the urine. A water deficit is confirmed if, with the administration of water, the elevated plasma $[Na]$ falls.

In many of the reports of cerebral hypernatraemia it is impossible to decide from the data given what the water balance was. The patients with hypernatraemia of Huggins and his co workers (1954) seem to have begun with a deficit of water of about one litre. Subsequently their intake of water may have been as little as two litres daily. Their exogenous osmolar load was about 610 m osm. We do not know what was the total excretion, urine volumes and specific gravities are not stated. The blood urea was high, and fell as the plasma $[Na]$ fell, when their intake of fluid was increased. In all

(Astrup and Jorgensen, 1954; Allott, 1957)

Failure of thirst. Even when losses of water do go unrecognized by the clinician, there is no danger of water-depletion as long as the patient is conscious and is able to drink.

insipidus the plasma [Na] is not usually very much raised, in a patient of ours, a man of 28 with sarcoidosis, the plasma [Na] was at times as high as 149 m equiv /l, but he was then very thirsty, and he would not tolerate the [Na] rising any higher. On the other hand, patients who are apathetic, weak, disorientated or unconscious may be unaware of thirst, or unable to respond to it. In these patients even normal losses of water may lead to water deficiency with hypernatraemia. It is not unusual to have elderly patients with cerebrovascular disease who tolerate a plasma [Na] of 150 m equiv /l without any complaint of thirst. But when they are given water they retain it, and their clinical and biochemical responses show they had a need for it. We do not know the possible sites of the lesions which may interfere with the sensation of thirst in these people. There is, however, some evidence that in man (Leaf and Mamby, 1952, Engstrom and Liebman, 1953), as in the rat (Stevenson, Welt and Orloff, 1950) and the goat (Andersson, 1957), neurological lesions may interfere with the normal sensation of thirst.

We have had the opportunity of studying a boy of ten who had had a large suprasellar craniopharyngioma removed by Mr C Langmaid. There was no evidence of diabetes insipidus before the operation. After the operation however, while he was in a stuporous state, his plasma [Na] ranged between 152 and 163 m equiv /l. It remained high even when he recovered, and was up and about, and receiving pitressin. The boy did not complain of thirst and we think the lack of thirst led to water deficiency and hypernatraemia. These are some of the values before and after he received pitressin —

	<i>Date</i>	<i>Plasma sodium m equiv /l</i>	<i>Urine vol ml per 24 hours</i>	<i>Specific gravity</i>
Before pitressin	7 Nov	161	1370	
After pitressin	21 Nov	156	860	
	25 Nov	156	1420	1.008

The urine volume and specific gravity while he was having pitressin suggest the treatment was inadequate, but he did

not respond, as does the ordinary case of diabetes insipidus, with thirst (He recovered spontaneously from his diabetes insipidus, and from his hypernatraemia, after three months). Although this type of hypernatraemia might be termed cerebral, it is in fact a water deficiency due to the breakdown of one of the mechanisms that normally ensure water balance.

Renal effects of water deficiency Before leaving the question of hypernatraemia due to water deficiency it may be noted that in many of the reported cases the disturbance apparently produced a disorder of tubular function, manifested by oliguria with isosthenuria or by the excretion of urine with a high pH in the presence of a systemic acidosis (Cooper and Crevier, 1952 (Case 4), Gordon and Goldner, 1957, Allott, 1957). This suggests that severe water deficiency may be accompanied by tubular damage. Allott (1959) noted a tubular degeneration in two of his cases *post mortem*.

A tubular damage would be expected if

least one of the patients

It is not possible to say

patients were water deficient but all of them had a high blood urea and in relation to this the urine volumes were certainly small. It is also possible that in some patients (e.g. Allott 1957) polyuria with hyposthenuria represented the diuretic phase of a tubular necrosis, itself the result of dehydration.

To sum up the question of 'cerebral' hypernatraemia, a failure of the thirst mechanism with or without a diabetes insipidus accounts for some of the cases that have been described and as Gordon and Goldner (1957) have ably illustrated unrecognized renal or extrarenal losses of fluid

the result of

if enough

- reestimated

small amount of water required to correct a severe deficit. Higgins and co workers (1954) gave up to four litres to the patients they thought were water deficient. We give nearly

this amount routinely Gordon and Goldner gave one of their two patients 8.24 litres in 24 hours and even this was not enough to bring down his plasma $[Na]$ to normal. As long as the plasma $[Na]$ remains high there can be no risk of water intoxication.

Other forms of hypernatraemia

It is possible to produce hypernatraemia by giving an excess of salt (McCance, 1956) though more usually this produces an isotonic expansion of the extracellular fluid with oedema.

The homeostatic mechanisms may be so adjusted as to maintain the plasma $[Na]$ at a high level. In experimental potassium deficiency the plasma $[Na]$ was over 150 m equiv/l although the absorption of sodium was small and the intake of water as much as eight litres a day in one subject (Fourman 1954). Hypernatraemia is often a feature of aldosteronism (Conn 1956) but whether or not this is the result of the associated potassium deficiency cannot be stated. Recently Zilver and Harris Jones (1957) have discussed the possibility of excessive adrenocortical activity producing hypernatraemia by a shift of sodium from cells to ECF.

Hyponatraemia

We may arbitrarily define hyponatraemia as a plasma $[Na]$ lower than 130 m equiv/l. It is obvious the concentration of sodium in the plasma may fall because of a reduction in the total amount of sodium in the ECF or because of an increase in the amount of water.

Salt deficiency

A reduction of the total amount of sodium in the ECF is the result of sodium deficiency.

We have already emphasized that the clinical effects of sodium deficiency are easily recognizable. Lack of salt is unlikely to arise unless through sweating, vomiting, diarrhoea or fistulous discharge, sodium is lost from the body because

the kidneys normally conserve sodium efficiently. For the same reason in sodium deficiency there is virtually no sodium in the urine. To this there is one exception, namely, when the sodium deficit is actually the result of continued loss through the kidney. This happens, of course, in Addison's disease, and in "salt losing nephritis". Furthermore, in certain patients with cerebral lesions persistent renal losses have been observed, even when the intake of sodium is much reduced (Welt *et al* 1952). The renal defect has been ascribed to a loss of neural impulses affecting proximal tubular function (Cort 1954). But the patient of Merrill, Murray and Harrison (1956) with malignant hypertension was able to maintain a normal sodium balance when his own kidneys were replaced by a kidney which was transplanted from his twin brother and therefore deprived of its nerve supply. It does not seem then that a loss of nervous impulses is alone responsible for a failure of the kidneys to conserve salt, though the renal nerves do play a part in the response to salt deprivation (Bricker *et al*, 1956) and to anoxia (Goldi, Kovách and Takács 1955a, b). The mechanism of the defect in cerebral salt wasting remains obscure. Water excess (see below) may produce a renal loss of sodium and some instances of so called salt wasting may therefore be examples of water retention.

Hyponatraemia from salt deficiency can of course, be corrected with salt.

W1

at

relative lack of salt and water. If only water is provided the [Na] falls. This state of affairs is seen most clearly in

For the patient while drinking copiously, produces only a small amount of concentrated urine containing very little sodium (Nelson, Rosenbaum and Strauss, 1951).

Water excess

Water excess is a well recognized cause of hyponatraemia when patients are given too much water while unable to excrete it at the normal rate (Wynn, 1956). This may happen in renal failure, in adrenal and pituitary insufficiency, and postoperatively, particularly after mitral valvotomy (Bruce *et al*, 1955). Hyponatraemia from this cause is usually obvious from the circumstances. Such patients may have no symptoms, sometimes they have the syndrome of water intoxication, with fits and other profound neurological disturbances. They may have hypertension, they certainly do not have hypotension. The face looks bloated, not drawn.

Both sodium deficiency and simple water excess respond to the administration of hypertonic saline with a rise in the plasma [Na] to normal which is subsequently maintained.

There remains for consideration a large group of cases where the hyponatraemia does not produce symptoms and its mechanism is obscure. Lickinton (1956) and McCrory and Macaulay (1957) have recently reviewed this problem. The hyponatraemia appears to be associated with an expanded volume of ECF, and the kidneys do not excrete water or retain sodium to bring back the tonicity of the plasma to normal (Leaf and Mamby, 1952).

There are at least two possible explanations. The first is that there is an abnormal stimulus to antidiuresis, say from the 'volume receptors', operating through the secretion of ADH or in some other way (Kleeman *et al*, 1955, Ginsburg and Brown, 1957). Pitressin given experimentally to normal people leads to a retention of water, a fall in the plasma [Na] and eventually an increased renal loss of sodium in spite of the low plasma [Na] (Leaf *et al*, 1953, Weston *et al*, 1953, Wrong, 1950).

The second possibility is that an abnormal hypotonicity of the cells determines the hypotonicity of the ECF (Sims *et al*, 1950, Rapoport, West and Brodsky, 1951).

McCrory and Macaulay (1957) described an infant with diffuse cerebral damage and hyponatraemia. Her ECF

volume was greater than normal. The infant did not excrete a dose of water at the normal rate and the authors thought she was secreting an excess of ADH. An excessive secretion of ADH would, of course, be appropriate only to a restricted fluid intake. When her fluid intake was restricted the plasma [Na] rose to normal.

Schwartz and co workers (1957) have recently suggested that an inappropriate secretion of ADH might account for the hyponatraemia in two patients with carcinoma of the bronchus whom they studied. They imply that there was an abnormal stimulation of the receptors for maintaining the volume of the body fluids. Their patients had normal renal and adrenal function, they excreted a normal amount of aldosterone. In one of them the plasma [Na] fell as low as 103 m equiv/l, but the extracellular volume, far from being reduced as in sodium deficiency, was expanded and there was no evidence of peripheral vascular failure. The urine was generally hypertonic to the plasma, and this is the principal argument adduced by Schwartz and co workers that these patients were producing too much ADH. The kidneys of these patients did not conserve sodium when their fluid intake was unrestricted though they did so when large amounts of salt retaining steroids were given. Schwartz and co workers do not

dose of
normal

urinary excretion and the plasma [Na] rose. Others have also described this response to water deprivation in hyponatraemia (see Edelman, 1956). It might be interpreted as the usual 'dehydration reaction'.

Some observations we have made on two patients with unexplained hyponatraemia are relevant.

Case reports

Albert, aged 62, was admitted on 25th May 1957 in status epilepticus accompanied by hyperpyrexia and heavy sweating. He had been up and about until then although he had had a right hemiparesis for two years which had become worse two months before admission. His

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of the low plasma [Na], on 19th June he excreted 210 m-equiv. of

Muscle analysis

The question whether the total sodium content of the body was low, or normal, but diluted by an excess of water in the ECF could be settled by an analysis of muscle.

Table 1

ANALYSES OF MUSCLE FROM THE TWO PATIENTS, COMPARED WITH
'NORMAL' VALUES

	Water per cent	m-equiv/kg fat free tissue Cl	Na	K
Albert	74.4	31.8	45.5	91.2
Ivor	79.1	27.2	47.0	89.3
Talso, Spafford and Blaw (1953)	77.6 \pm 0.6	19.1 \pm 3.0	33.7 \pm 0.4	94.0 \pm 5.9
Wilson (1955)	77.5	25.6 \pm 5.1	49.0 \pm 6.0	92.3 \pm 7.6
Barnes, Gordon and Cope (1957)	80.9 \pm 1.6	23.1 \pm 6.5	43.6 \pm 1.1	91.3 \pm 8.3

ANALYSIS OF PLASMA TAKEN FROM THE TWO PATIENTS AT THE TIME
OF THE MUSCLE BIOPSY

	m-equiv/l.		
	Cl	Na	K
Albert	89.6	124	5.5
Ivor	87.6	124	3.7

The specimens were taken from paralysed muscles in both patients. The electrolyte contents are shown in Table 1, with "normal" values for specimens taken from anaesthetized

blood pressure was 180/80. His fits were rapidly controlled, but he then had a bilateral spastic paralysis with extensor plantar responses, and never regained consciousness. On the second day he stopped breathing and respiration had to be maintained with a Beaver respirator for 12 hours. Subsequently he had a purulent bronchopneumonia and on the fourth day a tracheotomy was done to enable a clear airway to be maintained by suction. The bladder was kept drained by a Foley catheter but the urine was not infected until the last days of his illness. He died on 11th August of bronchopneumonia.

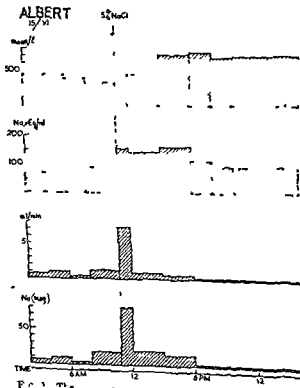
At post mortem there was a large area of softening in the left temporal lobe. The vessels of the circle of Willis were very atheromatous. There was evidence of an earlier hypertension, the left ventricle was hypertrophied to a thickness of 22 mm compared to 8 mm in the right ventricle, and the kidneys showed hypertensive changes. There was remarkably little evidence of infection in them although there was a purulent cystitis.

Albert was certainly water deficient in the early days of his illness.

blood was 55 per cent. He was then given six litres of water in two days, the packed cell volume fell to 41 per cent and the plasma [Na] fell to 128 m equiv/l. Subsequently his plasma [Na] fluctuated between 130 and 110 m equiv/l. The blood urea was 34 mg per 100 ml and the creatinine clearance 70 ml/min.

Ivor, aged 54, was admitted on 11th June 1957 having been ill for 18 days with acute peripheral neuropathy affecting mainly the motor nerves and accompanied by an enlargement of the liver. The plasma albumin (2nd July) was 2.9, and the total protein 6 g per 100 ml. The cause of his illness was not discovered. In the next five days he developed a partial respiratory paralysis with bronchopneumonia. His blood pressure, which had been normal, fell to 90/60. Subsequently he was fed by tube, and his purulent bronchial secretion was aspirated through a tracheostomy. At the end of June he began slowly to recover and was taking some food by mouth on 4th July, but almost immediately had a severe relapse. Tube feeding continued until the end of July, by which time he was able to move his limbs, though they were stiff.

tonic saline (Crawford and Ludemann, 1951; Birchard, Rosenbaum and Strauss, 1953, Papper *et al*, 1956), and depends, of course, on the liberation of ADH (Holland and Stead, 1951)



Water deprivation

When fluid was withheld for 19 hours both patients produced a urine of small volume and high osmolality (Table 1)

patients The potassium content was normal The sodium content, far from being lower than normal was in fact at the upper limits of the normal The chloride content was similarly high For this to happen with a low concentration of sodium in ECF, the amount of ECF in the muscle samples must have been larger than normal

Hypertonic saline

The infusion of hypertonic saline produced only a transient increase in the plasma [Na]

The response was studied in detail in Albert He had 500 ml of 5 per cent sodium chloride (436 m equiv) infused over about three hours on 15th June when his plasma [Na] was initially 127 m equiv /l (Fig 1)

The immediate response to this infusion was an osmotic diuresis with an output of 7.3 ml/min of urine containing 330 m osm and 155 m equiv of sodium per litre During the infusion he excreted 80 m equiv of sodium The plasma [Na] increased to 143 m equiv /l during the infusion and was 138 m equiv /l at the end In the following 21 hours he responded quite differently He excreted only 5.5 m equiv of sodium and his urine flow fell to 0.2 ml/min with a concentration of 696 m osm /l He was thus retaining water and diluting the sodium he had retained Three days later his plasma [Na] was again only 130 m equiv /l

Ivor had infusions of 300 ml of 5 per cent sodium chloride on 22nd June and 510 ml on 24th June We did not make very detailed studies of his response but the plasma [Na] before and after the second infusion was 113 and 115 m equiv /l During the first three hours of this infusion when he had received 190 m equiv he excreted only 30 m equiv Both the infusions were followed by a retention of water

These are not the responses one would expect from salt depleted patients (Black Platt and Stanbury, 1950) They imply that the osmolality of the body water was being maintained even at the expense of increasing the volume of the extracellular fluid This is the normal response to hyper

tonic saline (Crawford and Ludemann, 1951, Birchard, Rosenbaum and Strauss, 1953, Papper *et al*, 1956), and depends, of course, on the liberation of ADH (Holland and Stead, 1951)

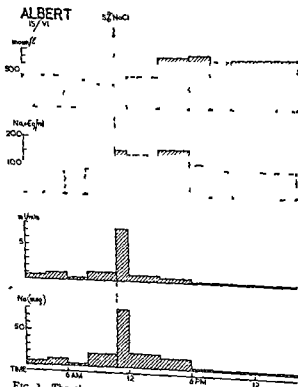


FIG 1 The changes in total sodium excretion urine flow sodium concentration and osmotic concentration of the urine after the infusion of 500 ml of 5 per cent sodium chloride (436 m-equiv)

Water deprivation

When fluid was withheld for 19 hours both patients produced a urine of small volume and high osmolarity. The

low The ratio of urine to plasma osmolalities, which can normally rise to about 4 with water deprivation, was 3.7 in Albert and 3.3 in Ivor The deprivation of water was associ-

Table II

EFFECTS OF DEPRIVING THE TWO PATIENTS OF WATER FOR 19 HOURS

<i>Changes in urine and plasma</i>	<i>Albert</i>	<i>Ivor</i>
Maximum urine concentration (m osm/l)	904	870
Flow at maximum concentration (ml/min)	0.27	0.11
[Na] (μ equiv/ml of urine)	22.6	14.6
Plasma (m osm/l)	243	267
Change in plasma ([Na] m equiv/l)	112-117	112-123

ated with a great reduction in the renal excretion of sodium, and the increases in the plasma [Na] were unexpectedly large They were not maintained however, for the plasma [Na] had returned to the original levels after 48 hours

Effect of water

The effect of a water load was adequately tested only in Albert, who on 15th July received one litre of water in 30 minutes, by stomach tube He excreted all of this water in less than three hours, achieving a diuresis of 7.3 ml/min, with an osmolal concentration of 54 m osm/l, and a sodium concentration of 4 m equiv/l These low concentrations are similar to the minimum values obtained in normal persons (Schoen, 1957) The values for the plasma sodium before and after the test were 115 and 112 m equiv/l Remarkably low osmolal concentrations were found twice in the 24 hour collections of urine from Albert The values, 153 and 168 m osm/l, were lower than in the plasma, in spite of the fact that at these times the plasma [Na] was exceptionally low, 104 m equiv/l, these values were obtained on the days immediately following administration of pitressin (see below)

We did not find any very low urinary concentrations in eight 24 hour collections from Ivor that were tested In one specimen an osmolal concentration of 215 m osm/l was the same as that of the plasma taken at that time

Effect of potassium chloride

In view of Laragh's (1954) findings of a rise in plasma [Na] with the administration of potassium chloride in patients with hyponatraemia we gave 100 m equiv of potassium chloride on two successive days to both the patients. There was no increase in the plasma [Na] and only a slight rise in the plasma [K].

The data so far reported show that the renal excretion of sodium could be made to vary from very small to very large amounts and in particular although sodium continued to be excreted while the plasma concentration was low, the kidneys were able to conserve sodium during the dehydration reaction. But a rise in the plasma [Na] produced by hypertonic saline was followed by retention of water which restored the osmolality of the plasma to its original level.

Effect of pitressin

All these results might be taken to show that these patients had an intact antidiuretic mechanism which operated to maintain their plasma osmolality at a lower level than normal. Their response however to exogenous ADH given as pitressin was quite unexpected.

After one litre of water by intragastric drip the patients received 100 m u of pitressin intravenously and 5 i u of pitressin in oil intramuscularly. Urine was collected in hourly periods for the following five hours the gastric drip was running throughout but the amounts given after the initial load were unfortunately not recorded. The results are shown in Table III. In Fig 2 they are compared with the results of water deprivation. Ivor began with a concentrated urine, but after the first hour the maximum osmolality achieved after pitressin was some 500 or 600 m osm. less than after dehydration. The effect of pitressin was tested a second time in Albert and he then passed urine with a concentration of 215 m osm/l that is lower even than his own hypotonic plasma. The low concentration of urine in these tests depended on the comparatively high urine flow, and not on a

reduced excretion of solutes. The rate of excretion of sodium and of solutes was actually higher than with dehydration, though lower than immediately before the pitressin was

Table III

EFFECTS OF PITRESSIN IN THE TWO PATIENTS WHILE THEIR HYDRATION WAS MAINTAINED

Changes in urine and plasma	Albert	Ivor
Maximum urine concentration (m osm /l)	280	197*
Flow at maximum concentration (ml /min)	1.5	2.4
[Na] (μ equiv /ml of urine)	11.2	60.2
Plasma (m osm /l)	233	217

* The results on the first collection (see Fig. 2) have been neglected

given. Glomerular filtration rates were not measured. The same batch of pitressin was shown to have normal activity in other subjects.

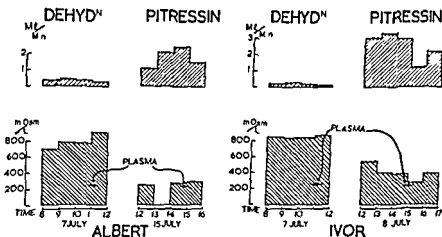


FIG. 2. Comparison of the changes in the flow and concentration of urine following deprivation of water and following pitressin and a water load.

The difference between the effects of water deprivation and pitressin is far greater than anything observed in normal people (Jones and de Wardener, 1956), and indeed indicates an almost complete failure to respond to pitressin in the

presence of a water load while the response to water deprivation was nearly normal. Pitressin was not entirely without effect on the urine flow since this diminished.

The failure of Albert and Ivor to respond to pitressin might represent the human counterpart of the experiments of Wesson and co workers (1950). Their dogs with an isotonic expansion of the ECF did not respond to pitressin.

We have mentioned that the failure of response was not a complete one and it therefore remains possible that the original expansion of the ECF represented an effect of the patients' own ADH as Schwartz and co workers (1957) postulated for their two cases. Although Schwartz and co workers do not remark on it there were occasions when their patient W. A. like Albert produced a hypotonic urine following an additional expansion of the ECF. These observations would be consistent with the suggestion that when the ECF is expanded beyond a certain point the kidneys become refractory to the action of ADH.

If we assume that an overproduction of ADH was responsible for the hypotonicity of the ECF in Albert and Ivor the alternatives previously suggested still remain: whether the stimulus to ADH production represented a homeostatic mechanism for maintaining a hypotonic ECF in two people who might have had hypotonic cells or whether it represented a response to an abnormal stimulation of some unidentified receptor.

Summary

The problem of hypernatraemia seems in general to be one of water deficiency. That of hyponatraemia is sometimes one of salt deficiency but often one of excessive dilution of the ECF with water. The latter seems to have been the fault in the two patients we studied. Muscle biopsies revealed normal or high sodium contents. In their responses to hypertonic saline water deprivation and water loading their homeostatic mechanisms were adjusted to maintain an abnormally large volume of ECF with low tonicity. Though

reduced excretion of solutes. The rate of excretion of sodium and of solutes was actually higher than with dehydration though lower than immediately before the pitressin was

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<i>Changes in urine and plasma</i>	<i>Albert</i>	<i>Ivor</i>
Maximum urine concentration (m osm/l)	~80	38*
Flow at maximum concentration (ml/min)	1.5	2.4
[Na] (μ equiv/ml of urine)	13.2	60.2
Plasma (m osm/l)	213	213

* The results on the first collection (see Fig. 2) have been neglected

given. Glomerular filtration rates were not measured. The same batch of pitressin was shown to have normal activity in other subjects.

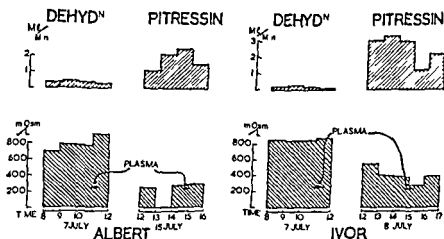


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they produced a hypertonic urine of low volume when deprived of water, they did not always produce a hypertonic urine with pitressin and water. Under certain circumstances, therefore, the kidney can excrete a hypotonic urine in the presence of pitressin while retaining its ability to respond normally to dehydration.

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DISCUSSION

take up any sodium that is in the gut
 ... A ... stools from ... with the salt losing type of adreno-
 examined
 ... to be much

... hyponatremia. The urine
One finds both
that might seem

intestine?

Desaulles I have no precise data.

Black I want to express agreement with Dr Fourman, because I think that none of the alleged clinical tests for water depletion, such as the

Fourman I think that is a very interesting comment. The very severe dehydrations probably do produce renal lesions and we have been wondering whether that accounts for the systemic acidosis, which is so often a prominent feature.

Wallace Chloride acidosis always occurs.

Fourman What is the plasma bicarbonate?

Wallace In our experience it is always low. Chloride is making bicarbonate forfeit its place in serum.

Desaulles Dr Fourman, was it possible to make steroid determinations in your case?

We have made an observation on animals that is not identical but may point in the same direction as the observation you have made. If

the sensitivity to pitressin

urine was normal. A Gowenlock in Manchester measured the aldosterone output in one of our patients and it was normal. We also did 17-ketosteroid assays as a crude measure of their corticoid output, and the results were normal. It is obvious that the hyponatraemia does not lead to a stimulation of the aldosterone output of the adrenal.

Desaulles Could this be given the same interpretation as the findings of Prader, Spahr and Neher (1955 *Schweiz med Wschr*, 85, 1085)? There may be some form of sodium losing syndrome.

Adolph It seems to me Dr Pourman that in order to show that there is something more to one of these syndromes than a lack of drinking behaviour or drinking response on the part of the individual, you have to perform your tests in a certain order: you have to be sure that the patient has plenty of water when you do the salt test and plenty of salt when you do the water test. Could you have switched the tests around and still obtained the same results?

Pourman The saline load was done three weeks before the dehydration. The dehydration preceded the pitressin by one day in one of the patients, by a week in the other patient. The pitressin test was accompanied by a load of water at the time. I do agree that one test can influence another but I do not think that they did in this instance.

Borst When a high or a low sodium concentration in the blood plasma is maintained we believe that this is almost always due to an insufficient circulation. This insufficiency often results from dehydration but it may have other causes such as cardiac failure or hypoproteinaemia. We found a high blood sodium in anaemic patients who had had recurrent haemorrhages from peptic ulcer. They had no free access to water and had been treated with abundant saline infusions: they had substantial oedema. During several days the urine contained less sodium than tap water. After a large transfusion of blood the sodium excretion started and the blood sodium fell to a normal level. Simultaneously, the output of water increased and the urea concentration of the urine which had been very high decreased. The counterpart was

A large blood transfusion elicited a considerable water diuresis and the blood sodium rose to normal, while the oedema fluid was excreted.

With both the high and the low sodium concentrations the circulation was inadequate. In the first instance the excess of sodium and a less considerable excess of water was excreted as soon as the normal blood volume was restored. In the second the rise in blood volume led to the

salt and water has an effect on the circulation. The problem is that an excess or an inadequacy of the circulation in patients cannot be measured in a satisfactory way. Since this factor cannot be disregarded we have to estimate it on the basis of indirect evidence.

GLANDULAR SECRETION OF ELECTROLYTES

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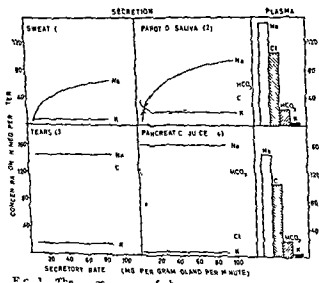
THE ducts or tubules of glands with external secretion are usually quite complex in structure and morphologically they differ to a considerable extent from gland to gland. It is, therefore, reasonable to assume that the ducts do not merely serve as pathways for the secretion formed in the acini, but that they contribute somehow to the elaboration of the final secretory product. This possibility has already been considered in the past century by Merkel (1883), mainly on morphological grounds, and by Werther (1886), who made a comparative investigation of the concentration of salt in various types of saliva. The results of these experiments were however inconclusive, and in 1950 Babkin restated the need for a study of the physiology of the glandular ducts. Since then certain advances have been made through comparative work, by the application of concepts from modern renal physiology and with the use of electrophysiological methods, relating changes in membrane potentials to ionic transport. It is the purpose of the present paper to review this work and to present a theory of the mechanism of glandular electrolyte secretion based on the available data.

Fig. 1 shows a comparison between the concentrations of the main electrolytes in sweat, parotid saliva, tears and pancreatic juice in relation to secretory rate calculated in milligrams per gram gland per minute. The following similarities and differences between the four secretory products are apparent from Fig. 1.

The Excretion of Sodium

In sweat and in parotid saliva the concentration of sodium is smaller than the concentration of sodium in plasma and

varies with the rate of secretion. With increasing secretory rate the concentration of sodium rises to about 60 m equiv/l in the sweat and to about 90 m equiv/l in the parotid saliva, but no definite maximum is reached in either secretion. This finding conforms with the old work of Heidenhain (1868), Langley and Fletcher (1889), Kittsteiner (1911, 1913), and Hancock. Whitehouse and Haldane (1929)



In tears and in pancreatic juice the concentration of sodium in secretion water is about equal to the concentration of sodium in plasma water and is independent of the rate of secretion.

The Excretion of Potassium

The concentration of potassium in all four secretions is independent of wide ranges of variation in secretory rate.

In parotid saliva however, a definite rise in potassium concentration is noted at rates smaller than 15 mg per gram gland per minute. This finding is in agreement with the results of Langstroth, McRae and Stavaky (1938) and Burgen (1956). A similar rise in potassium concentration possibly occurs at low rates of sweat secretion (Kuno 1956) but could not be demonstrated with the experimental technique employed by Schwartz and Thaysen (1956). In the two other secretions a rise in potassium concentration at low secretory rates has never been observed.

The Excretion of Anions

The main anion of sweat and tears is chloride. This anion accounts for about 80 per cent of the sum of the concentrations of sodium and potassium in the tear fluid. Chloride concentration of sweat is not depicted in Fig. 1, but Iocke and his co-workers (1951) found the following relation: $\text{sodium} = 1.12 \text{ chloride} + 3 \text{ m equiv./l.}$

The chief anion of parotid saliva and pancreatic juice is bicarbonate. With increasing secretory rate the concentration of bicarbonate rises in both secretions and reaches a maximum of about 60 m equiv./l. in parotid saliva and about 90–130 m equiv./l. in pancreatic juice. When this maximum concentration (which is subject to individual variation) has been arrived at the concentration of bicarbonate remains independent of further increases in the rate of secretion. The concentration of chloride varies inversely with that of bicarbonate. In both secretions and at all rates the sums of the concentrations of the two anions equal about 80–90 per cent of the sums of the concentrations of sodium and potassium.

The following hypothesis has been put forward to explain the demonstrated differences in the excretion of the main cations. In all four glands a precursor solution is formed in which the concentration of sodium is independent of the rate of precursor formation. In the sweat and parotid glands but not in the other two glands sodium is consequently reabsorbed by a process of a limited maximal capacity (Thaysen

Thorn and Schwartz, 1954, Thaysen, 1955, Schwartz and Thaysen, 1956, Hulmer and Forwell, 1956, Bro Rasmussen, Killmann and Thaysen, 1956) Like sodium, potassium is transferred into the precursor at a constant concentration, but it is not reabsorbed in any of the glands. The rise in potassium concentration at the low secretory rates in parotid saliva (and in sweat?) may be secondary to reabsorption of water from the precursor as indicated by Langstroth, McRae and Stavaky (1938) and by Thaysen, Thorn and Schwartz (1954) and/or to an exchange between sodium and potassium ions during the process of sodium reabsorption.

Table I

COMPARISON BETWEEN THE CALCULATED CONCENTRATIONS OF SODIUM AND POTASSIUM IN THE PRECURSOR SECRETIONS OF FOUR SECRETORY PRODUCTS AND THE CONCENTRATIONS OF THE SAME IONS IN PLASMA WATER

	SWEAT	PAROTID	LACRYMAL	PANCREATIC	PLASMA WATER
Na	79	112	146	161	160
K	9	19	15	5	5
SUM	88	131	161	166	165

Fig. 2 shows a linear regression of the rate of sodium excretion in parotid saliva on the rate of secretion. According to the above hypothesis the values for slope and intercept in Fig. 2 can be interpreted to mean that sodium is transferred into the precursor solution at the rate of 0.112 microequivalents per mg. of saliva discharged and that 2.4 microequivalents are subsequently reabsorbed per gram gland per minute. The sodium concentration of the sweat precursor has been calculated in a similar manner from the data of Schwartz and Thaysen (1956) and the values are compared to those of the other secretions and to plasma water in Table I. According to Table I the sums of the concentrations of sodium and potassium in the presecretions of saliva and sweat are lower than the sums of the concentrations of the same ions in the two other secretions and in plasma water. No other cations

are present in parotid saliva and in sweat in sufficiently large concentration to make up for this difference. Judging from the results of Table I, the production of sweat and parotid saliva should therefore involve secretion of hypotonic precursor solutions, a process which *a priori* does not appear very likely

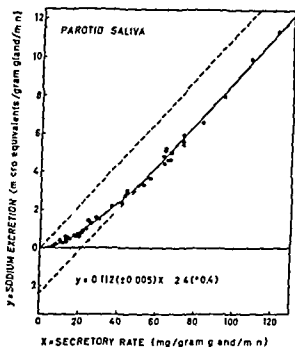


FIG. 2 The relation between the rate of sodium excretion in parotid saliva (in microequivalents

gland per minute

It must be emphasized, however, that the calculated figures for precursor sodium concentration (and sodium reabsorption) in the sweat and parotid glands underestimate actual values, since the regressions for sodium excretion on secretory rate have been fitted to points which approach, but do not reach, a rectilinear relationship within the observed range (cf Fig. 2). One explanation for this considerable splay in

the observed values from the asymptote could be that there is a certain back diffusion of water in the sequence of active sodium reabsorption. As demonstrated below there is reasonable qualitative evidence to suggest that water is, in fact, reabsorbed from the precursors of sweat and parotid saliva.

Fig 3 illustrates that the concentration of urea in sweat, tears, and parotid saliva remains proportional to the con-

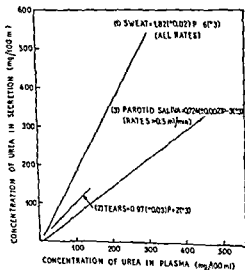


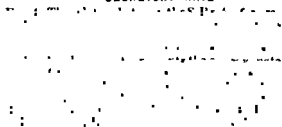
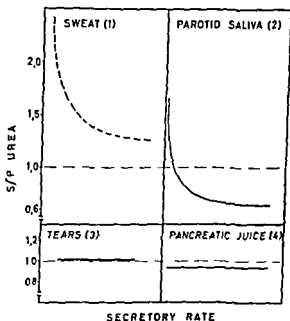
FIG 3 The relation between the concentration

centration of urea in the plasma within a wide range of variation in the latter. This finding indicates that urea is excreted in these secretions by a process of simple diffusion and not via a specific secretory mechanism. by increasing load as a tracer for the glands in a similar

and the glomerular nephron

Fig. 4 shows the relationship between the S/P (secretion/plasma) concentration ratio for urea and the rate of secretion of sweat, parotid saliva, tears and pancreatic juice.

In tears and in pancreatic juice there is apparently diffusion equilibrium between the secretion and the plasma at all



rates of glandular activity. On the basis of these findings no statement can be made about the existence or non-existence of an internal circulation of water in these glands.

In sweat and in parotid saliva S/P urea varies with the rate of secretion. In the sweat S/P urea decreases from 2 or 3 at the low secretory rates to about 1 when sweating

becomes profuse (Araki and Ando, 1953, Bulmer, 1957) In parotid saliva the ratio decreases from about 1.6 at low rates of secretion to about 0.6 when the flow of saliva is brisk (Albrechtsen and Thaysen, 1955) Since no specific secretory mechanism for urea exists in either gland, it is reasonable to conclude that urea which is diffusing into the gland with some precursor solution, is raised to a concentration greater than that of the plasma by reabsorption of water from the precursor in a region of the gland which is less permeable to urea than the site of precursor formation The rate of change in S/P urea with secretory rate suggests that water reabsorption represents a relatively constant quantity at all rates of precursor formation and it is not unreasonable to assume that the reabsorption of water occurs as a mere passive sequence of active sodium reabsorption

Quantitative information about precursor formation and water reabsorption can however, hardly be gained from these results or from similar 'clearance' studies with other solutes Morphological and physiological evidence strongly argues against the possibility that the secretion precursor represents an ultrafiltrate of the plasma like the urine precursor of the glomerular nephron A 'glandular inulin' probably does not exist and it is quite possible that exact knowledge about the composition of the precursor secretions and about the manner in which they are modified as they flow down the glandular ducts can only be obtained by micropuncture techniques

However Lundberg (1955, 1957a, b, c) working on the

has shown that sodium is reabsorbed from a precursor secretion in some of the duct possessing glands

In the submaxillary gland, which produces a secretion in which sodium concentration varies with secretory rate in about the same manner as in parotid saliv.

gland is activated by stimulation of the chorda. A similar internal duct negativity could not be demonstrated in the sublingual gland (Lundberg, 1957a), which (like the lacrimal and pancreatic glands) produces a secretion that is isotonic with the plasma and has a sodium concentration of about 150 m equiv/l. Provided that the potential changes on stimulation can be regarded as the electrical signal of ionic transport, Lundberg (1957a) concludes that there is a net transport of cation from the lumen to the blood side in the ducts of the submaxillary gland, but not in the sublingual gland. Although the composition of the submaxillary secretion was not measured simultaneously with the duct potential, the latter appears large enough for it to be accepted that the reabsorption of anion is merely a passive sequence of active cation transport.

With one microelectrode inserted into acinous cells and the other electrode on the gland surface, Lundberg (1955, 1957a) detected a considerable increase in the negativity of the acinous cells on stimulation of the submaxillary as well as of the sublingual gland. The lumen of the acini, likewise, becomes negative as compared to the morphological interior, but this negativity decreases slightly with continued stimulation of the gland. These potential changes may be due to a net transport of anion from the blood side into the glandular lumen. In another paper Lundberg (1957c) directly demonstrated this anionic dependence of secretion and secretory potentials in the perfused sublingual gland. Substitution of sodium chloride with sodium nitrate or sodium thiocyanate caused the secretion to stop almost entirely and decreased the potential changes. The secretory response and the potentials reverted to normal when sodium chloride was again added to the perfusate.

On the basis of the experiments quoted in the present report, it appears reasonable to suggest the following mechanism for the secretion of electrolytes and water by the duct possessing glands. Active outward transport of anions is a main factor in the formation of the secretory products of all

glands. In some glands the chief anion transported is chloride (sweat, tears, sublingual saliva), in others bicarbonate ions are added in varying proportion, possibly due to the presence of carbonic anhydrase in the cells (pancreatic juice, parotid saliva, submaxillary saliva). It is reasonable to assume that water moves in a merely passive sequence of ionic transport from the blood side into the glandular lumen, and that the presecretions of all glands are isotonic or nearly isotonic.

In certain glands (sweat, parotid and submaxillary) sodium is reabsorbed from the precursor secretion as it flows down the glandular duct system and it is likely that anions move from duct lumen to the blood side in a passive sequence of the active sodium reabsorption. The chief anion reabsorbed in this manner appears to be chloride, independently of whether the primary secretion contains primarily chloride or primarily bicarbonate ions. It can be seen from a glance at Fig. 1 that the parotid and the pancreatic glands apparently form presecretions of qualitatively similar composition, and that the main difference in the anionic pattern of the final secretory products is that chloride ions have been removed from the saliva precursor. As a consequence of active sodium reabsorption a certain quantity of water is, moreover, diffusing back into the blood stream, although it is obvious that water reabsorption does not occur isototically as in the

According to Fig. 5 it is, however, not unreasonable to suggest that sodium reabsorption is located in the striated intralobular ducts. Striated epithelium is present in the parotid and submaxillary glands which apparently reabsorb sodium but it is absent in the sublingual, pancreatic and lacrimal glands which show no evidence of sodium reabsorption. The precursor secretions are probably formed by the acini as well as by the cuboidal epithelium of the intercalary ducts, the former producing a viscous secretion with a high concentration of organic material, the latter a

watery secretion with a low concentration of organic material (cf. Babkin, 1950). With respect to the sweat gland it is

SWEAT	PAROTIS	SUBMAX.	SUBLING.	PANCREAS	LACRYMAL
$S_{Na} < EC_{Na}$			$S_{Na} = EC_{Na}$		
S_{Na} varies with secretory rate			S_{Na} independent of secretory rate		

suggested that precursor formation is located in the coil, whereas reabsorption of sodium takes place in the duct.

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Amer. J.

J. exp. Med., 98, 293

DISCUSSION

There is no doubt that the concept of the glandular secretion of electrolytes is a new one. It is a concept that is still in its infancy, but it is a concept that is worth pursuing. It is a concept that is worth pursuing because it is a concept that is worth pursuing.

At the
concept

rates of secretion. Certainly this is not the case in the parotid gland (Fig 4, p 68). Conversely, I do not venture to claim that the cells in the duct are impermeable to an extent that would completely prevent urea from diffusing back into the blood stream along the concentration gradient created by water reabsorption. But the amount of urea diffu-

slowly over others. This difference is not important when one measures total body water as the volume of distribution of urea, because one waits until complete equilibrium has been established before the measurement is made. But the difference is important in the rate-dependent process of secretion, where the time available for diffusion becomes limiting.

Karlonen In prolonged sweating the potassium concentration is higher to start with and then gradually decreases. There is no similar change in sodium or chloride and that would agree quite well with the reabsorption and consequent storing of potassium in the tubule, whereas sodium and chloride are not stored (Ahlman *et al* (1953) *Acta endocr., Copenhagen*, 12, 140).

Thaysen Yes, the first sample of sweat obtained after stimulation may have a higher potassium concentration than the following ones. One reason for this may be that the first sample is contaminated with cellular debris, sebum and sweat residues on the skin surface.

speculated that the vigorous flow of saliva, caused by stimulation, "pushed out" first a small amount of secretion, which had been produced

sodium concentration falls. The net amount of sodium lost from the

Ann. (1950) J. appl. Physiol., 8, 621)

Adolph Can somebody clarify the reports that tears are very hypertonic when they are formed?

Dawson I did some analyses a long time ago, and we discovered that the chloride concentration was equal to that of the blood. It is a very difficult problem obtaining tears, because you have got to make the person cry very hard to get enough to do an analysis.

Thompson Is that so?

and not just filtered from the plasma. One then wonders whether epithelium does not similarly push out potassium in exchange for the sodium which is being reabsorbed—the sort of mechanism that is possibly under aldosterone control.

Thaysen: An exchange mechanism between sodium and potassium ions at the site of sodium reabsorption is certainly a very likely possibility.

change for reabsorbed sodium ions. Similarly, the adrenal steroids may have a dual site of action in the glands. In contradistinction to the situation

As regards your comment about the rice diet, sodium depletion, induced by a low sodium diet, causes the concentration of sodium to

and incomplete as compared to that of the kidney tubule (Robinson *et al.* (1955), *J. appl. Physiol.*, 8, 159, Thorn *et al.* (1956) *J. appl. Physiol.*, 9, 477).

Karvonen: Can anyone comment on the statistical finding that men

findings in animals, not in sweat but in urine, but I have absolutely no explanation for it. It is just an observed fact.

Talbot: I wonder if those who are commenting on the sodium, chloride and potassium concentrations in sweat all have in mind the relationship

between rate of sweating and the concentration, because it varies enormously.

Thaysen · Yes, that is very important. Secretory rate must be controlled in all work on electrolyte composition of secretions, and compara-

comparative work it is a prerogative, but also the number of fu

Exp. Med., 40, 129)

and not just filtered from the plasma. One then wonders whether epith-

Thaysen: An exchange mechanism between sodium and potassium ions at the site of sodium reabsorption is certainly a very likely possibility. This may be one factor causing the potassium concentration of the final secretory product to exceed that of the plasma. However, glands which

in concentration on which depends is that of the plasma in some in ex- is may situa- on the gland

As regards your comment about the rice diet, sodium depletion, induced by a low sodium diet, causes the concentration of sodium to

and incomplete as compared to that of the kidney tubule (Robinson *et al.* (1955). *J. appl. Physiol.*, 8, 159, Thorn *et al.* (1956). *J. appl. Physiol.*, 9, 477).

explanation for it. It is just an observed fact.

Talbot: I wonder if those who are commenting on the sodium, chloride and potassium concentrations in sweat all have in mind the relationship

and salt. There does not appear to be any inability to secrete ADH or adrenocortical hormones, though it is possible that the infant does lack the power to adjust the amounts secreted with any precision. The endocrinological situation, therefore, is essentially one of target organ insensitivity due to immaturity.

An interesting hypothesis relating to neonatal weight loss has been put forward by Gans and Thompson (1957). These workers measured the urine output and its content of oestrogens and 17 hydroxycorticosteroids in six normal male neonates during the first few days of life. The findings were similar in all the infants. Large amounts of oestriol (up to a milligram or more) were excreted on the first post partum day, the quantity falling rapidly during the next two or three days to the order of 1 or 2 μg by the sixth day. Oestrone and oestradiol were found to the extent of 1–2 μg during the first and second days and then disappeared. There was a decreasing excretion of urine during the first three to five days, and by the end of this time, postnatal weight loss had ceased. The excretion of 17 hydroxycorticosteroids showed only minor fluctuations throughout. The specific gravity of the urine was low at first but became more concentrated as the excess of water was excreted in spite of the fact that fluid intake was increasing during this time.

Gans and Thompson suggest that part at least of the hydraemia of the newborn infant is due to water retention caused by the high circulating oestrogen level—the oestrogens being, of course, of maternal origin. As the oestrogens are excreted the fluid excess is eliminated.

Adrenal hyperplasia

Adrenal hyperplasia is a disorder with a definite predilection for the female sex. In Wilkins' series (Wilkins, 1950)

about one out of these patients have a tendency to loss of sodium and

HORMONAL ASPECTS OF WATER AND ELECTROLYTE METABOLISM IN RELATION TO AGE AND SEX

G I M SWYER

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NEARLY all the hormones may have some influence on water and electrolyte metabolism. However, for most of them this effect is indirect and occurs only under highly abnormal circumstances. Thus, the dehydration which exists in uncontrolled diabetes mellitus or in hyperparathyroidism is the result, respectively, of gross deficiency of insulin or excess of parathormone, and certainly does not point to any physiological rôle of these hormones in water metabolism. The same is essentially true of thyroid hormone and though perhaps with reservations, of the sex hormones and gonadotrophins. Only posterior pituitary antidiuretic hormone (ADH) and certain of the adrenocortical steroids are directly concerned with the day to day and minute to minute adjustments needed to maintain fluid and electrolyte homeostasis in mammals. The major details of this hormonal control are well known and it is not necessary to relate them here. It is proposed, on the other hand, to examine how the influence of hormones on fluid and electrolyte balance differs at various ages and in the two sexes. In general it is fair to say that little attention has been paid to considerations such as these, and for the most part knowledge is meagre.

In Infancy

Fluid and electrolyte control is notoriously inefficient at birth and during the first few weeks or so of life. The late development of the loop of Henle is generally considered to be responsible for this (Hubble, 1957) the infant kidney being unable, in consequence, to vary tubular reabsorption of water

and salt. There does not appear to be any inability to secrete ADH or adrenocortical hormones, though it is possible that the infant does lack the power to adjust the amounts secreted with any precision. The endocrinological situation, therefore, is essentially one of target organ insensitivity due to immaturity.

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about one fourth of these patients have a tendency to loss of sodium and

to elevation of the plasma potassium, as a result of which early death may occur from dehydration and circulatory collapse, or from cardiac arrest due to hyperkalaemia. Once again, the number of females affected is some three times that of males.

The mechanism for this sodium loss is not understood. Very likely there is a defect in aldosterone synthesis, but it is also possible that some of the abnormal steroids produced by the hyperplastic adrenals may actually cause sodium loss. It is well known that surprisingly large amounts of sodium chloride and cortisone acetate (DOCA) may be needed to remedy the electrolyte defects in these infants, suggesting that more than mere replacement of deficient hormone is necessary. However, the response to 9α fluorohydrocortisone, together with cortisone, may be far more satisfactory. In a $1\frac{1}{2}$ year old patient of the writer's, a female pseudohermaphrodite with the salt losing disorder, 10 mg daily of DOCA intramuscularly, together with large sodium supplements, was necessary to maintain electrolyte balance. With only 0.25 mg of 9α fluorohydrocortisone daily by mouth, it was possible to maintain balance with no sodium supplement at all.

A small proportion of patients with adrenal hyperplasia (about 6 per cent) may show hypertension. It is possible that in these there is actually sodium retention. Bongiovanni and Eberlein (1955) have demonstrated in such a patient a defect in the synthesis of cortisol different from that usually found in adrenal hyperplasia. This patient was producing increased amounts of cortisone and 17 hydroxycortisone, it is thought probable that these steroids were responsible for the hypertension.

Changes in Relation to Adolescence

Knowledge of endocrine changes in relation to adolescence is rather sketchy. It is ably summarized by Tanner (1955). The impact of these changes on fluid and electrolyte metabolism is somewhat obscure. Certain morphological changes of

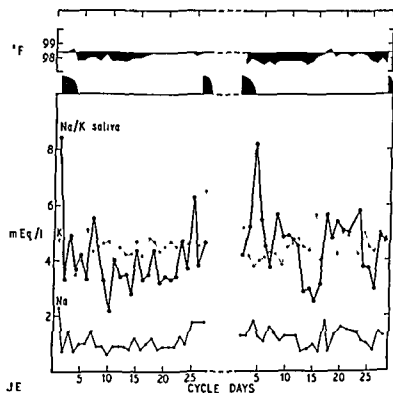
possible significance occur. Thus, a considerable growth spurt in the weight of the adrenal gland, more in boys than in girls, has been observed. It is almost entirely due to growth of the cortex. The weight of the thyroid also shows an adolescent spurt, but without any sex difference. Scanty data on hormone excretion indicate a slow increase in the excretion of oestrogen in both boys and girls during childhood, with a marked increase at puberty in the case of girls, while in boys the rate of increase hitherto manifested is merely maintained. Androgen excretion is similar in the two sexes before puberty, after puberty there is a marked rise in the case of boys, but a not unimportant rise also occurs in girls, no doubt as a result of increased adrenocortical activity. There is a gradual rise in the rate of secretion of adrenal corticoids, without sex difference, from birth to maturity. The increase appears to be proportionate to body size, without any adolescent spurt. The blood level of 17 hydroxycorticosteroids is much the same at all ages and the responsiveness of the adrenals to stimulation by adrenocorticotrophic hormone is also unaffected by age, except, of course, in so far as the adrenal glands are smaller in children than in adults. A steady fall in the serum protein bound iodine over the years six to 15 parallels the fall in basal metabolic rate, and the precise

Effects of the Menstrual Cycle

An important sex difference is introduced by the cyclic variations in hypothalamic-pituitary-ovarian (and perhaps adrenocortical) function which determine the menstrual cycle in females. It might well be expected that these would lead to important fluctuations in fluid and electrolyte balance.

Variations in body fluid during the menstrual cycle have been mentioned in connection with the study of the

reported weight gains of up to 14 lbs. at or during menstruation in two women. Several other writers (see Chesley and Hellman, 1957) have concluded that approximately 30 per cent of women have weight gains associated with menstruation. The suggestion that premenstrual weight gain is due to



water and salt retention, mediated by oestrogens, is due to Thorn, Nelson and Thorn (1938). Long and Zuckerman (1937) postulated a rôle of adrenal salt-retaining hormones in the electrolyte imbalance causing premenstrual fluid retention.

In a recent investigation, Chesley and Hellman (1957)

studied 23 normal young women and found that in one third of them the weight was maximal during the premenstrual eight days—in accordance with earlier writers. Closer analysis, however, failed to substantiate the physiological basis of such weight gains, since, when they did occur, they

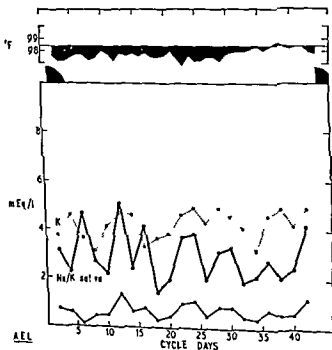


FIG. 2. A long but ovular, cycle in a normal woman

were slight and were not repeated from one cycle to the next. It was further shown that the incidence of premenstrual weight gain was the same as would be expected.

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compatible with increased adrenal salt retaining hormone secretion during the premenstrual phase

The present author's own limited studies on salivary and urinary Na/K ratios in the menstrual cycle have been directed

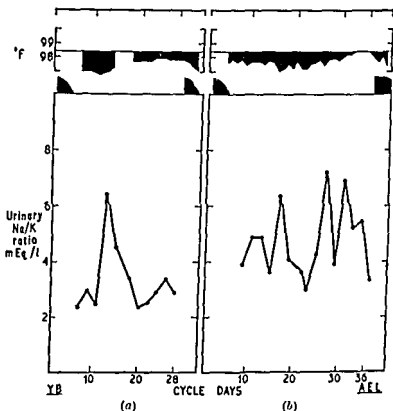


FIG. 3 Urinary Na/K ratios in two normal women. In (a) there appears to be a peak at about the time of ovulation. In (b) the ratio appears to be higher during the second half of the cycle.

mainly towards an attempt at elucidating the basis for so called premenstrual tension which is widely supposed to depend upon premenstrual salt and fluid retention (see, for example, Greene and Dalton, 1953, who consider an increased oestradiol/progesterone ratio to be largely responsible). The findings are in agreement with those of Chesley and

Hellman (1957) in that no precise pattern of variation in salivary or urinary sodium and potassium concentrations or Na/K ratios, either in normal women or in those complaining of premenstrual tension, has been discovered

Fig 1 shows two cycles from a normal woman the Na/K

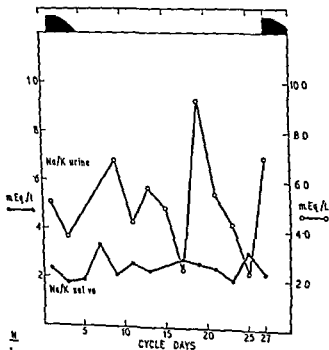


FIG 4 Urinary and salivary Na/K ratios compared in a woman who experienced premenstrual tension

ratio appears to be high at the start of both cycles and there is a distinct fall (mainly due to increased potassium secretion) at what may be judged from the basal temperature record to be the time of ovulation in the second cycle

Fig 2 shows a long but ovular cycle in another normal patient (AEL) No convincing pattern is discernible Fig 3b shows the urinary Na/K ratios in another cycle from

patient A.E.L. If anything, the ratio is higher in the second half of the cycle—i.e. sodium retention is less premenstrually. In Fig. 3a, the urinary Na/K ratio appears to rise sharply just at the time of ovulation—i.e. at the time of an oestrogen peak, when, according to the usual view, the tendency should be towards sodium retention.

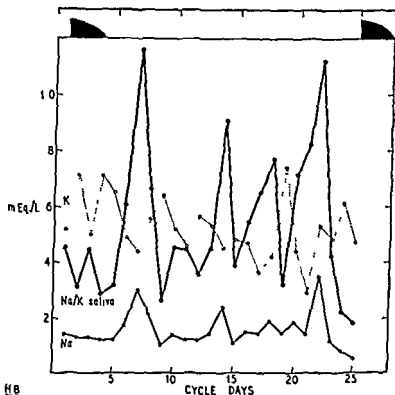
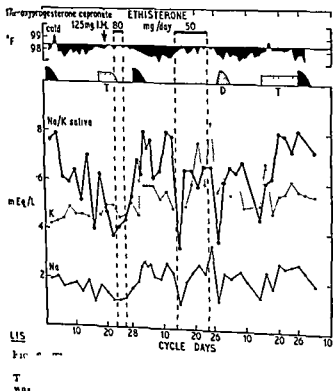


FIG. 5. Salivary sodium and potassium concentrations and ratios in a woman who experienced premenstrual tension.

Figs. 4–6 relate to women who experienced definite premenstrual tension. In Fig. 4 the salivary and urinary Na/K ratios are compared. The latter (note that its scale is ten times that of the salivary Na/K ratio) is much more variable than the former, and neither shows any definite pattern. Certainly there is no evidence of sodium retention premenstrually. Fig. 5 shows the salivary Na/K ratios in another

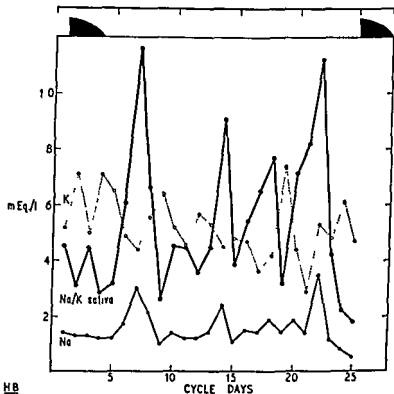
patient; they fluctuate violently but show no evidence of premenstrual sodium retention.

Fig. 6 shows three consecutive cycles in a patient who experienced quite severe premenstrual tension. In the first



cycle, the Na/K ratio in the saliva was definitely lower, due to a lower sodium concentration, in the second half of the cycle. An injection of 125 mg of 17α oxyprogesterone capronate intramuscularly failed to affect the symptoms, but when ethisterone, 80 mg. daily by mouth, was started three days later the tension disappeared, in spite of the Na/K ratio

patient A.E.L. If anything, the ratio is higher in the second half of the cycle—i.e. sodium retention is less premenstrually. In Fig. 3a, the urinary Na/K ratio appears to rise sharply just at the time of ovulation—i.e. at the time of an oestrogen peak, when, according to the usual view, the tendency should be towards sodium retention.



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FIG. 5. Salivary sodium and potassium concentrations and ratios in a woman who experienced premenstrual tension.

Figs. 4-6 relate to women who experienced definite premenstrual tension. In Fig. 4 the salivary and urinary Na/K ratios are compared. The latter (note that its scale is ten times that of the salivary Na/K ratio) is much more variable than the former, and neither shows any definite pattern. Certainly there is no evidence of sodium retention premenstrually. Fig. 5 shows the salivary Na/K ratios in another

quantity during pregnancy has been shown by numerous balance studies (see Rinsler and Rigby, 1957 for references) Chesley and Boog (1943) found an increased thiocyanate space in normal pregnancy, the increase being still greater in pre-eclamptic toxæmia. From this it was concluded that much of the sodium retention was due to expansion of the extracellular fluid (ECF) compartment. However, Gray and Plentl (1954), using a sodium isotope dilution technique, found little change in the sodium space and total exchangeable sodium in normal pregnancy. They observed a total gain of some 500 m equiv. of sodium during the last six months of pregnancy, which they felt could be accounted for by the products of gestation and the expanded maternal blood volume. The maintenance of an essentially unchanged non-pregnant sodium space during normal pregnancy, despite the rise in plasma volume, suggests that there is little change in ECF.

The gain of sodium and water, with maintenance of a normal total exchangeable sodium value and with an increased thiocyanate space, provides indirect evidence that in normal pregnancy there is an alteration of cell permeability with an increased maternal storage of intracellular sodium and water. This is

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of the F and plasma volumes. It has been demonstrated by Bartter and co-workers (1956) that a fall in ECF volume without change in tonicity leads to a rise in aldosterone excretion. Such a rise in aldosterone excretion occurs in pregnancy (Venning and Dyrenfurth, 1956, Venning *et al.*, 1957; Rinsler and Rigby, 1957) and may form part of a homeostatic mechanism.

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expanded ECF compartment
expansion of this compartment was shown by Bartter and

remaining low In the next cycle, 50 mg ethisterone daily was given from the 14th day of the cycle There was no tension (though the succeeding period was painful) Yet again the Na/K ratio appears to have been on the whole lower in the second half of the cycle In the third cycle, no treatment was given, the usual premenstrual tension appeared but this time the premenstrual Na/K ratios were the highest in the cycle

It must be confessed that the writer does not know how to interpret these findings, beyond concluding that they do not provide evidence for theories currently held to account for premenstrual tension and its relief (which in the writer's experience, is by no means invariable) with progesterone or its analogues

Pregnancy

In no physiological circumstances do such profound hormonal changes occur as in pregnancy The output of oestrogens rises some thousandfold of progesterone ten to twentyfold and of adrenocortical and thyroid hormones to less impressive but still significantly increased levels A new hormone, chorionic gonadotrophin, found only in pregnancy, of foetal and therefore partly paternal origin—a 'foreign protein', to some extent—appears in the circulation immediately after implantation, rises to striking levels by about the 60th day of gestation and then as rapidly falls to about one quarter the maximum level during the remainder of pregnancy The sum total of these changes is to produce a substantial degree of fluid and sodium retention in all pregnant patients Oedema is of course common, its association with hypertension, with or without albuminuria to give pre-eclamptic toxæmia, is also not uncommon Toxæmia is for the obstetrician, one of the remaining major problems he has to face Its pathogenesis continues in obscurity, in spite of extensive research

Only one or two aspects of this vast problem will be dealt with here

That water and sodium are retained in considerable

conclusions, of possible relevance to our main theme, are as follows

Oestrogens In men, the output of oestrogens remains relatively constant with increasing age, in women, on the other hand, the output declines between the ages of 40 and 60 years, reaching a level somewhat below that of men and thereafter remaining constant. Of the separate fractions, oestrone and oestradiol decline slowly in men, accompanied by an increase in oestriol which makes the total oestrogen output appear constant, in women the most marked decline in earlier decades is in oestriol output, the least marked in that of oestrone, while in the later decades further small declines in oestrone and oestradiol are accompanied by an apparent increase in oestriol. Oestriol is a metabolite, not a secretory product as the other two may be, its increase with advancing age may therefore be due to lesser destruction of secreted oestrogen.

Neutral Steroids The rate of decline of 17 ketosteroids is similar in both sexes. The urinary ketonic androgens are higher in men than in women and decline more steeply in the former particularly during the earlier decades. During these decades the decline of androgens is steeper than that of 17 ketosteroids so that with advancing age the ratio of 17

ketosteroids to 17 ketonic androgens declines more rapidly than that of the less androgenically active 17 ketosteroids. Though this might have been expected for men as a result of declining testicular function, it is perhaps more surprising in women and suggests a decrease in output of either adrenal or ovarian androgens, or both.

The ratio of androgens to oestrogens is higher for men than for women at all decades until the ninth.

The output of adrenal corticosteroids is rather higher in men than in women at all ages and varies but little with age. In contrast the non ketonic steroids, a mixture of substances

co workers (1956) to cause a fall in urinary aldosterone excretion in normal persons. In the pre eclamptic patients studied by Rinsler and Rigby (1957), the aldosterone outputs were considerably less than those at the same stage of normal pregnancy and it was concluded that this was because of the expanded ECF compartment. The output of aldosterone in these toxæmic patients is less, for a given urinary Na/K ratio, than in the normal group, yet despite the low aldosterone output, sodium retention is maintained or increased. This suggests that a mechanism other than that of aldosterone secretion may be responsible for the sodium retention of pre eclamptic toxæmia.

Labour, especially if prolonged, is another aspect of pregnancy in which electrolyte disturbance may assume importance. Hawkins and Nixon (1957) have demonstrated a consistent loss of plasma water and increase in plasma specific gravity after only 20 hours of labour, indicating a state of dehydration long before the appearance of clinical signs. In addition, they found an increase in plasma sodium and a decrease in chloride and potassium. This, they suggest, is due to increased renal excretion of chlorides necessitated by the disturbance of acid base balance due to ketosis resulting from shortage of available glycogen. After 48 hours of labour, a striking fall in plasma potassium and in circulating eosinophils was seen. This is consistent with increased adrenocortical activity, such as is known to occur after surgical operations (MacPhee, 1953). In labour, this fall in plasma potassium may be particularly important because of its influence on uterine contraction. It is very probable that potassium depletion in long labours materially adds to the inefficiency of an already inert uterus.

Changes in Steroid Metabolism in Ageing Men and Women

The most extensive study of this subject has been made by the Worcester group (Pincus *et al*, 1955). Certain of their

CHESEBURY, L. C., and HELLMAN, L. M. (1957). *Amer. J. Obstet. Gynec.*, 74, 582

DYKE, H. B. VAN, ADAMSON, K., and ENGEL, S. L. (1935). *Recent*

129.

.. Brit.

Итак, мы получили, что $f_{\text{max}} = 2 \cdot 10^4$ н/м.

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11. *Journal of the American Medical Association*, 273:1225-1226, 1995

1. *Chlorophyll a* and *Chlorophyll b* were determined by the method of Arar and Collins (1971) using a Shimadzu UV-160U ultraviolet-visible spectrophotometer. The concentration of chlorophyll was expressed in $\mu\text{g mL}^{-1}$ of the sample.

"I don't know if I can do it," he said.

1943, 11, 21.

RIVELER, M G, and RIGBY, B (1957) *Brit med J*, 2, 966.

THESE THÈSES SONT DÉPOSÉES À LA BIBLIOTHÈQUE NATIONALE

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14, 1987

Average U. H. Pathways M. G. = 7.60

11. *Journal of the American Medical Association*, 273:1265-1266, 1995

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1. *Journal of the American Medical Association*, 1997; 278: 1039-1044.

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1. *Journal of the American Medical Association*, 277, 1996, 1033-1037.

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Strayer No, but I am very interested to hear of these changes.

scribner Dr. Sawyer, who -

Q. Now we did not see any other people in the room, did we?

It was hoped that it had

...the [sic] that if the cl

of doubtful origin, part adrenocortical and part perhaps gonadal, decline with age much as do the 17-ketosteroids. Thus the outputs of the various classes of neutral steroids change with age in dissimilar fashion. Close study of the data suggests that the steroids of adrenal origin are less affected by age than are those derived from the gonads, but that adrenal steroids are not uniform in behaviour in this respect.

This differential behaviour is clearly shown by the various α ketosteroids. The 11 deoxy steroids, androsterone and aetiocholanolone, decrease regularly and markedly with advancing age, in both men and women. In contrast, the 11-oxygenated 17 ketosteroids decrease much less markedly with increasing age in both sexes. The 11-oxyaetiocholanolones decrease least of all, these substances derive chiefly from cortisol and its metabolites.

To evaluate the significance for fluid and electrolyte control of these hormonal changes in ageing men and women is none too easy. The most important of the above mentioned hormones from this point of view are the adrenal corticosteroids, the output of which changes least. Beyond that simple statement it is unsafe to venture.

Nothing has hitherto been said about the rôle of antidiuretic hormone of the posterior pituitary in the control of electrolyte and fluid metabolism under the various circumstances discussed above. Though it is true that numerous reports have appeared in the literature implicating ADH in a variety of pathological states characterized by oliguria and oedema, it is the opinion of van Dyke, Adamsons and Engel (1955) that "the assays used to support this belief are so grossly inaccurate as to make valueless any conclusions that have been reached". If we may accept that opinion, nothing further need be said.

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inappropriate imposition, here the hypotonicity of the extracellular fluid is accompanied by a swelling of the cells. An "appropriate" fall in tonicity and increase in volume of the extracellular fluid is not associated with these symptoms. The patients I mentioned earlier do not have evidence of water intoxication.

After every stress, these patients with hyponatraemia returned to their original low concentration of extracellular fluid. One feels that the concentration is determined by the cells—a new steady state. We do believe that this low concentration of the extracellular fluid must be the result of a low osmotic pressure of the cells. There are obviously different kinds of hypotonicity of the extracellular fluid, with and without symptoms of water intoxication. When there are symptoms, the cells are swollen. Miss Leeson and I have been wondering whether a lack of symptoms means the cells are not swollen, but merely hypotonic.

Siryer: I was referring to the opposite problem, namely that in labour dehydration is accompanied by lack of potassium. Presumably this increase in specific gravity of the plasma and the apparent loss of plasma potassium would not be consistent with normal functioning of the cells.

with people who were keeping themselves on an ordinary kind of régime they would show up in spite of any day-to-day variations. That is certainly a deficiency in our studies, but I do not think it entirely invalidates them.

Thaysen How were the Na/K ratios in the saliva done?

Swyer They were obtained by collecting saliva first thing in the morning, as nearly as possible at the same time each day, for a fixed length of time (five minutes). In one series, the first five minutes was collected, and in another series the first five minutes was discarded and the second five minutes collected, as I understand there is something significant in that. We were unable to see any difference at all when done in these two

volume. It did not seem to make any difference at all, but I do agree that some of the variables might have been inadequately controlled.

Thaysen I believe that you might find the ratio very reproducible when you use a standard secretory rate.

Talbot Dr. Swyer, you mentioned something about a will o'-the-wisp, sodium diuretic hormone of adrenal origin. Do you believe in its existence, and if so, have you or any of those here a solid notion as to the nature of the beast?

Swyer I certainly have no solid notion. It is an idea that has been mooted to account for the apparent inability of normal amounts of sodium retaining hormone to counteract the sodium loss. I know there have been very active searches for it, and that large amounts are found in the salt losing type of adrenal hyperplasia.

Desaulles We have worked quite a lot on this problem and we have got something which is derived from the adrenal, but what it is we do not really know. Dr. Wettstein (1958 *Iva*, 29, in press) has just described how he found it and how he is working on it, but that is as far as we have got.

Adolph I would like to raise a general problem which Dr. Swyer brought up. How is one to judge whether in labour there is dehydration? All the criteria by which we can judge of the existence of dehy-

McCance - It is a question of definition. Do you mean by dehydration a rise in the tonicity of the extracellular fluid due to an increase in the

and Kowntree, L. G. (1922). *Arch intern. Med*, 29, 306) exemplifies an inappropriate imposition, here the hypotonicity of the extracellular fluid is accompanied by a swelling of the cells. An "appropriate" fall in tonicity and increase in volume of the extracellular fluid is not associated with shrinkage of cells. Cells do not have

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Sayer - High
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invalidates them

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and in another series the first five minutes was discarded and the second five minutes collected, as I understand there is something significant in that. We were unable to see any difference at all when done in these two

that the estimation of the Na/K ratio permits one to dispense with the necessity for measuring secretory rate

Swyer Another thing we did was to measure the volumes which were produced in this fixed time, and try to correct for the variations in volume. It did not seem to make any difference at all, but I do agree that some of the variables might have been inadequately controlled

Thaysen I believe that you might find the ratio very reproducible when you use a standard secretory rate

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how he found it and how he is working on it, but that is as far as we have got

Adolph I would like to raise a general problem which Dr Swyer described of dehydration, and I about it. or super-hydration, as transitory states of the organism?

retain water before birth and still excretes high amounts of oestrogens after birth, that the persisting influence of the mother's oestrogens in the early days of life might be the explanation of the infant's poor response to a water load.

Adolph This oestrogenic influence seems to me a very interesting possibility. Has anyone any data on the influence of the maternal hormones upon water balances or exchanges?

Fourman Another question is whether oestrogens do inhibit the

handling of the water load since that extends for the best part of the first year, or so I understand

McCance No, only about 14 days, I believe

Adolph I think I can clarify this contradiction of ages to some extent. If you read the literature up to 1923 you learn that in the first year the

water load is great, and within 90 days even as great as in the adult human, if one bases water load and excretion on unit body weight.

Soyer Does this also apply to resistance to dehydration and handling of electrolytes?

Adolph I do not think we have any good data on the resistance to dehydration. We know much less about hydropaemia than we do about superhydration.

Young I think there is a much simpler explanation for the young infant's rapid rise in serum potassium under conditions of stress. The

hydration. I have no real proof of this, but all neonates becoming dehydrated very quickly show a high serum potassium level.

Milne In these cases in babies with high serum potassium, is the myocardium less sensitive to the hyperkalaemia? This could be inferred from the work of Widdowson and McCance (1956, *Clin Sci*, 15, 361) on serum potassium in foetal pigs. Anyone with experience of hyperkalaemia in acute renal failure in adults would find very severe ECG changes long before the serum potassium reached 10 m equiv./l, and death usually occurs very shortly after the potassium reaches 10 m equiv./l. These high figures rather startle me, I would like to know what is happening to the ECG during the period of hyperkalaemia.

Davson The effect of potassium on the heart is linked with that of calcium. It may be that over long periods the calcium might rise too and tend to compensate for the raised potassium.

Scribner We have made some studies on dogs and we could not greatly increase the tolerance of the dog to hyperkalaemia by giving calcium. Large doses of calcium increased tolerance no more than 1 m equiv./l.

Adolph The response of the heart to potassium is a very frightening experience

young males, it is a very frightening experience to see the heart misbehaving with both the clinical effects and the ECG changes of hyperkalaemia.

McCance You seem to have found something in which the infant

of infants, sometimes the physiologist's point of view has made the

logy are borne in mind

There is one point I should like to make which refers to the papers by Prof Adolph and Dr Swyer. It seems to me, since the baby tends to

GENERAL DISCUSSION

Richet Dr Thaysen mercury poisoning is supposed to inhibit

substance?

Thaysen I have not done any experiments of this kind myself,

Richet Dr Desaulles has reminded me that during chronic mercuric poisoning acrodynia for instance, there is an increase in sweating

Thaysen That might be due to a cerebral effect of chronic mercury poisoning rather than to a local effect of the mercury directly on the glands

Dalson It is rather a fortunate accident that the mercurials are diuretics and that they have that specific action on the kidney

parallel increase in the plasma magnesium, cellular magnesium also went up but rather less

Richet We have made determinations of plasma magnesium in more than 200 patients during acute and chronic renal failure. During acute renal failure there is always an increase in plasma magnesium concentration. Our technique with yellow titanium gives normal values of 1.5-1.7 m-equiv/l. In acute renal failure we sometimes get 3.0-3.5 m-equiv/l serum magnesium. In contrast, serum

tends to delay the development of serious dehydration during the neonatal period. This process coupled with other attributes might enable some newborn infants to survive total thirsting as long as an adult.

Heller: I seem to remember that what Gans and Thompson showed was that there was a decrease of body water in the infant which was correlated with the excretion of maternal oestrogens, but this does not establish a causal relationship.

to the other.

Wallace: Dr Swyer, what about the situation of a diabetic woman and her baby? In a great number of instances there is a very intense water retention.

Swyer: I can counter that by saying what about the baby of a pre-diabetic mother? It shows just the same changes before the mother has diabetes. I do not think we know why the prediabetic mother has a large baby—there have been suggestions that it is due to excess growth hormone secretion by the mother, but there is no very convincing evidence.

Wallace: This kind of baby generally seems to have a great deal of water in him—more water than in equivalent weight normal babies.

Swyer: That is very true. The baby is large but it is not postmature—indeed, it behaves more like a premature.

Wallace: Is that an oestrogen effect?

Swyer: I do not think we know.

Wallace: Very often during these discussions the words "inefficient" and "immature" have been used to describe the newborn infant. Mr Peter Riekham in his book, 'The Metabolic Response to Neonatal Surgery' (1957 Harvard University Press), develops the point of view that the newborn infant is tolerant of adverse experiences such as fasting, thirsting and surgical trauma. Despite the fact that the newborn has an extra load of water in his body and a low metabolic rate he does seem to have a certain toughness that at a later date is not so evident. "Immaturity" and "inefficiency" may not be synonymous.

and salt management that we are talking about today—we tend to find any evidence that the small children react any worse than their children and adults.

Daison Was there also a control on whether salts were being absorbed when they say that five time isotonicity would have stopped it? Just the fact that the skin absorbs water does not mean that salts are not absorbed as well

skin by a layer of air. The type of salt used determines the amount of water vapour in the air. The results by this technique agree with the hypertonic solution studies.

Hingerty What salts have been investigated?

Scribner Sucrose potassium chloride sodium chloride. The phenomenon is believed to be purely an osmotic effect.

Borst Before the war Viennese clinicians reported on considerable absorption of water by the skin in heart failure. The prognosis could even be determined by studying the rate of absorption. Dutch

potassium is increased in only 20 per cent of our patients. We have

potassium remains normal for a long time

McCance That agrees with observations Miss Watchorn and I made in 1932 (*Biochem J*, 26, 54). We generally found that the serum magnesium was high in chronic renal failure and indeed searched for such cases when we wanted high values for our ultrafiltration experiments

Scribner I want to bring to your attention the work done by Dr Konrad Buettner, professor in the Division of Climatology at the University of Washington, Seattle (1953 *J appl Physiol*, 6, 229). His observations bear on the sweating data that we have heard and also on considerations of cellular tonicity. If you study water

trations of sodium chloride solution, the skin will take up water until a concentration which is five times isotonic is reached. The mechanism of absorption is not known and there has been no work to elucidate why this occurs. The rate of absorption in an adult human is about 20 ml/hr for the total skin, and is correspondingly less for

low rates of sweating, data on electrolytes in sweat may be abnormally high throughout due to this absorption, and there is some chance that by the proper control of conditions you may be able to absorb water in survival experiments at sea, since sea water is only three times isotonic.

Darson What happens to the water? Is it immediately carried away by the capillaries?

Scribner Yes. Deuterium studies have shown that Ten—twenty ml/m²/hr are the actual figures for the absorption.

Talbot In the last war in survival ration studies we immersed some very dehydrated volunteer subjects in the equivalent of sea

Darson: Was there also a control on whether salts were being absorbed, when they say that five time isotonicity would have stopped it? Just the fact that the skin absorbs water does not mean that salts are not absorbed as well.

BODY WATER COMPARTMENTS THROUGHOUT THE LIFESPAN*

H. VICTOR PARKER, KNUD H. OLESEN, JAMES McMURREY
and BENT FRIIS HANSEN

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Harvard Medical School Boston and
Queen Louise's Children's Hospital Copenhagen*

Our first knowledge of the composition of the body was acquired during the last decades of the nineteenth century. The methods used were desiccation and chemical analysis which allowed the determination of the contents of water and electrolytes in carcasses or in single organs. With the recent introduction of the dilution methods a new field of study has grown up based on the *in vivo* measurements of the total quantities of body water and its partitions. Direct dilution methods are now available for the measurement of total body water and of the extracellular water. The intracellular water is calculated as the difference between total body water and extracellular water and is thus a derived value (Moore *et al.*, 1956).

A few comments should be made about the methods and the evaluation of the measurements. In the material presented the total body water has been determined as the volume of dilution of deuterium oxide. In the children the extracellular water has been measured as the volume of dilution of thio sulphate and in the adult groups as the volume of distribution of radioactive bromide corrected for red cell bromide, for the relative water contents of plasma and interstitial water, and for the Donnan effect. As the volume of dilution of thio

* This work was supported by a grant from the United States Atomic Energy Commission to the Peter Bent Brigham Hospital (AT-(30-1)-733).

sulphate is smaller than the corrected volume of dilution of radiobromide the values for extracellular volumes will not be directly comparable for the children and the adults. The same will apply to the calculated intracellular water. All the methods used are reproducible within the 5 per cent range. As the absolute quantities measured are difficult to compare from one individual to another it has become customary to express the results as relative values. The standard of reference used is the body weight as this standard in our experience has been the most simple. In the interpretation it is important to realize that a rather large biological variation appears within groups of the same age and sex.

Although the study of the body water compartments throughout the lifespan is still fragmentary, certain trends in relation to age and sex have appeared. It will be the purpose of this paper to outline these features in a description of the body water compartments during the three main phases of life: growth, maturity and ageing.

Growth

Growth implies a variety of fundamental processes: cell multiplication, increase in cell size, accumulation of extracellular material, increase in fat and minerals.

The alterations in the body water compartments during growth have been studied by Friis Hansen (1956). From a series of 93 normal children studied with deuterium oxide with thiosulphate or with both, a series of 31 individuals with simultaneous measurements of all three water compartments will be presented.

It appears from Table I that the absolute amounts of total body water, of extracellular water and of intracellular water demonstrate an increase throughout infancy and childhood. It is seen that the intracellular water rises more markedly than the extracellular water.

In Table II the three measurements are given as percentages of body weight. The total body water shows a relative decrease throughout infancy and childhood with a most marked

BODY WATER COMPARTMENTS THROUGHOUT THE LIFESPAN*

H. VICTOR PARKER, KNUD H. OLSEN, JAMES McMURREY
and BENT FRIIS-HANSEN

Our first knowledge of the composition of the body was acquired during the last decades of the nineteenth century. The methods used were desiccation and chemical analysis which allowed the determination of the contents of water and electrolytes in carcasses or in single organs. With the recent introduction of the dilution methods a new field of study has grown up based on the *in vivo* measurements of the total quantities of body water and its partitions. Direct dilution methods are now available for the measurement of total body water and of the extracellular water. The intracellular water is calculated as the difference between total body water and extracellular water and is thus a derived value (Moore *et al.*, 1956).

A few comments should be made about the methods and the evaluation of the measurements. In the material presented the total body water has been determined as the volume of dilution of deuterium oxide. In the children the extracellular water has been measured as the volume of dilution of thio sulphate and in the adult groups as the volume of distribution of radioactive bromide corrected for red cell bromide, for the relative water contents of plasma and interstitial water, and for the Donnan effect. As the volume of dilution of thio

* This work was supported by a grant from the United States Atomic Energy Commission to the Peter Bent Brigham Hospital (AT-(30-1)-797) and by the Surgeon General Department of the Army, through a contract (DA-49-007-472) with Harvard Medical School and sponsored by the Commission on Liver Disease, Armed Forces Epidemiological Board.

Within the body water compartments the measurements with thiosulphate demonstrated a relative decrease of extracellular water during growth. A similar degree of decrement in extracellular space with advancing age has been reported by Ely and Sutow (1932) using the thiocyanate method, and by Cheek (1954) using the corrected bromide space. The relative values for intracellular water in the series presented stayed about the same throughout infancy and childhood. No similar investigations are available in the literature, but it is interesting that Corsa and co workers (1956) found that the total exchangeable potassium as related to body weight stayed the same throughout infancy and childhood. As about 95-98 per cent of the exchangeable potassium must be present within the cells their results can be taken as corroborative evidence for Fris Hansen's (1956) findings of the relative constancy of the intracellular water.

An alteration in the interrelationship between the extracellular and intracellular water during growth thus appears. When the extracellular water is expressed as a percentage of total body water the extracellular compartment decreases from 55 per cent in the youngest group to 38 per cent and 28 per cent in the two oldest groups, again reflecting the relative decrease of the extracellular water. This altered relationship between the extra- and intracellular water is another important facet in the body compositional changes during growth.

The alterations during growth could be produced in two ways (1) They could be due to a proportional alteration in

22

Histochemical studies are helpful in the interpretation of this problem. Kerpel Fronius (1937) found in studies of muscular tissue from human newborn babies and from adults a relative increase in intracellular phase during growth, whereas such a change did not appear in the skin or in the central nervous tissue. Kerpel Fronius also drew attention to the fact that the total muscle water had increased from

decrease during the first two years of life. The relative decrease in extracellular water is more marked than the decrease in total body water. The intracellular water demonstrates about the same relative value throughout childhood. It should be mentioned that no sex difference appeared in this

Table I

BODY WATER COMPARTMENTS IN CHILDREN ABSOLUTE VALUES

| Age | Water compartments in litres | | | Number of subjects |
|-----------|------------------------------|------|-------|--------------------|
| | TBW | ECW | ICW | |
| 0-11 days | 2.65 | 1.45 | 1.20 | 5 |
| 11-180 | 3.10 | 1.42 | 1.68 | 9 |
| 1-2 years | 5.40 | 2.36 | 3.04 | 7 |
| 2-7 | 8.96 | 3.40 | 5.56 | 9 |
| 7-14 | 27.62 | 7.52 | 20.10 | 1 |

series. The tendencies found in this group are similar to the findings in the larger group including cases with single measurements of total body water or of extracellular volume. A statistical analysis of the larger group has shown that most of the differences between the age groups are significant.

Table II

BODY WATER COMPARTMENTS IN CHILDREN RELATIVE VALUES

| Age | Values in per cent of body weight | | | Number of subjects |
|-----------|-----------------------------------|------|------|--------------------|
| | TBW | ECW | ICW | |
| 0-11 days | 76.4 | 41.6 | 74.8 | 5 |
| 11-180 | 72.8 | 34.9 | 37.9 | 9 |
| 1-2 years | 62.2 | 27.5 | 31.7 | 7 |
| 2-7 | 65.5 | 25.6 | 36.9 | 9 |
| 7-14 | 64.2 | 17.5 | 46.7 | 1 |

The relative decrease in total body water with advancing age indicates a relative increase in total body solids, i.e. cell solids, mineral solids and body fat. The total body solids thus represent the fraction of the body which demonstrates the highest degree of absolute increase during growth. This increase in total body solids represents one important facet in the alterations in body composition with advancing age.

for the relative water contents of plasma and interstitial water, and for the Donnan effect. As the extracellular water according to the method applied here shows a higher normal value than is obtained with the thiosulphate method the results for extracellular and intracellular water in this series will not be directly comparable to the findings in the group of children.

Table III

BODY WATER COMPARTMENTS IN ADULTS ABSOLUTE VALUES

| Sex | Age range | Body weight
kg | Water compartments in litres | | |
|---------|-----------|-------------------|------------------------------|------|------|
| | | | TBW | ECW | ICW |
| Males | 23-34 | 72.5 | 38.9 | 16.8 | 22.1 |
| Females | 23-51 | 59.3 | 28.7 | 13.3 | 15.4 |

The absolute average values for total body water, extracellular water and intracellular water appear in Table III. As expected all values are higher in the males than in the females, corresponding to the higher average weight in the male group. Most of the difference in total body water is accounted for by the difference in intracellular water.

Table IV

BODY WATER COMPARTMENTS IN ADULTS RELATIVE VALUES

| Sex | Age | Weight kg | Water compartments in per cent of body weight with standard error of the mean | | |
|---------|-------|-----------|---|------------|------------|
| | | | TBW | ECW | ICW |
| Males | 23-34 | 72.5 | 54.3 | 23.4 | 30.9 |
| | | | ± 1.39 | ± 0.64 | ± 0.89 |
| Females | 23-51 | 59.3 | 48.6 | 22.7 | 25.9 |
| | | | ± 1.47 | ± 0.54 | ± 0.96 |

In Table IV the average values are given in per cent of body weight. The males contain 54.3 per cent of total body water whereas the females contain 48.6 per cent. This difference is statistically significant ($P=0.01$). The relative values for the extracellular water are very close to one another. The intracellular water amounts to 30.9 per cent in the males and to 25.9 per cent in the females. This difference is statistically significant ($0.01 > P > 0.001$).

29 per cent of total body water in the newborn baby to 51 per cent of total body water in the adult and he stressed that an increase in total muscular tissue rich in intracellular phase was a prominent feature in the alterations in body composition during growth

Yannet and Darrow (1938) found in their studies of cats a relative increase in intracellular phase during growth in muscles, whereas only very small alterations appeared in liver tissue or in brain tissue. In studies of growing chickens Barlow and Manery (1954) reported a similar relative increase in the intracellular phase in muscular tissue.

It appears from these studies that the alterations measured with the dilution methods must be results of a development varying quantitatively and qualitatively from one tissue to another.

In conclusion the alterations in body composition during growth can be described as a disproportional increase in total body solids, total body water, extracellular water, and intracellular water. When the values are related to body weight the following trends are seen during growth: a decrease in total body water, an increase in total body solids, a decrease in extracellular water, and a relative constancy in intracellular water. When the water compartments are related to total body water the trend is for a relative decrease in extracellular water and a relative increase in intracellular water.

Maturity

The body water compartments in adults will be described with particular reference to the sex difference.

The material presented comprises ten normal males and ten normal females at ages from 23 to 54 years, average age in the middle thirties. The series was studied by H. V. Parker in Dr. Francis D. Moore's laboratory, Peter Bent Brigham Hospital, Boston (McMurrey *et al.*, 1958). The methods applied were: total body water was determined with deuterium oxide, the extracellular water was measured as the radiobromide space, which was corrected for red cell bromide,

It appears from the series that males have a higher relative content of body water than females, confirming the results with the deuterium oxide method reported by ¹³ ¹⁴ ¹⁵ ¹⁶ ¹⁷ ¹⁸ ¹⁹ ²⁰ ²¹ ²² ²³ ²⁴ ²⁵ ²⁶ ²⁷ ²⁸ ²⁹ ³⁰ ³¹ ³² ³³ ³⁴ ³⁵ ³⁶ ³⁷ ³⁸ ³⁹ ⁴⁰ ⁴¹ ⁴² ⁴³ ⁴⁴ ⁴⁵ ⁴⁶ ⁴⁷ ⁴⁸ ⁴⁹ ⁵⁰ ⁵¹ ⁵² ⁵³ ⁵⁴ ⁵⁵ ⁵⁶ ⁵⁷ ⁵⁸ ⁵⁹ ⁶⁰ ⁶¹ ⁶² ⁶³ ⁶⁴ ⁶⁵ ⁶⁶ ⁶⁷ ⁶⁸ ⁶⁹ ⁷⁰ ⁷¹ ⁷² ⁷³ ⁷⁴ ⁷⁵ ⁷⁶ ⁷⁷ ⁷⁸ ⁷⁹ ⁸⁰ ⁸¹ ⁸² ⁸³ ⁸⁴ ⁸⁵ ⁸⁶ ⁸⁷ ⁸⁸ ⁸⁹ ⁹⁰ ⁹¹ ⁹² ⁹³ ⁹⁴ ⁹⁵ ⁹⁶ ⁹⁷ ⁹⁸ ⁹⁹ ¹⁰⁰ ¹⁰¹ ¹⁰² ¹⁰³ ¹⁰⁴ ¹⁰⁵ ¹⁰⁶ ¹⁰⁷ ¹⁰⁸ ¹⁰⁹ ¹¹⁰ ¹¹¹ ¹¹² ¹¹³ ¹¹⁴ ¹¹⁵ ¹¹⁶ ¹¹⁷ ¹¹⁸ ¹¹⁹ ¹²⁰ ¹²¹ ¹²² ¹²³ ¹²⁴ ¹²⁵ ¹²⁶ ¹²⁷ ¹²⁸ ¹²⁹ ¹³⁰ ¹³¹ ¹³² ¹³³ ¹³⁴ ¹³⁵ ¹³⁶ ¹³⁷ ¹³⁸ ¹³⁹ ¹⁴⁰ ¹⁴¹ ¹⁴² ¹⁴³ ¹⁴⁴ ¹⁴⁵ ¹⁴⁶ ¹⁴⁷ ¹⁴⁸ ¹⁴⁹ ¹⁵⁰ ¹⁵¹ ¹⁵² ¹⁵³ ¹⁵⁴ ¹⁵⁵ ¹⁵⁶ ¹⁵⁷ ¹⁵⁸ ¹⁵⁹ ¹⁶⁰ ¹⁶¹ ¹⁶² ¹⁶³ ¹⁶⁴ ¹⁶⁵ ¹⁶⁶ ¹⁶⁷ ¹⁶⁸ ¹⁶⁹ ¹⁷⁰ ¹⁷¹ ¹⁷² ¹⁷³ ¹⁷⁴ ¹⁷⁵ ¹⁷⁶ ¹⁷⁷ ¹⁷⁸ ¹⁷⁹ ¹⁸⁰ ¹⁸¹ ¹⁸² ¹⁸³ ¹⁸⁴ ¹⁸⁵ ¹⁸⁶ ¹⁸⁷ ¹⁸⁸ ¹⁸⁹ ¹⁹⁰ ¹⁹¹ ¹⁹² ¹⁹³ ¹⁹⁴ ¹⁹⁵ ¹⁹⁶ ¹⁹⁷ ¹⁹⁸ ¹⁹⁹ ²⁰⁰ ²⁰¹ ²⁰² ²⁰³ ²⁰⁴ ²⁰⁵ ²⁰⁶ ²⁰⁷ ²⁰⁸ ²⁰⁹ ²¹⁰ ²¹¹ ²¹² ²¹³ ²¹⁴ ²¹⁵ ²¹⁶ ²¹⁷ ²¹⁸ ²¹⁹ ²²⁰ ²²¹ ²²² ²²³ ²²⁴ ²²⁵ ²²⁶ ²²⁷ ²²⁸ ²²⁹ ²³⁰ ²³¹ ²³² ²³³ ²³⁴ ²³⁵ ²³⁶ ²³⁷ ²³⁸ ²³⁹ ²⁴⁰ ²⁴¹ ²⁴² ²⁴³ 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The similarity of the relative values for the extracellular water and dissimilarity of the relative intracellular water volumes in the two sexes gains further support from other parts of the same study. As is seen in Table V, simultaneous studies of total exchangeable sodium and potassium were carried out in these patients according to the method described by Moore and co workers (1956). The total exchangeable sodium which was determined through an independent measurement demonstrates relative values very similar in the two sexes. As about 85 per cent of the total exchangeable sodium can be accounted for in the extracellular space the findings can be taken as supportive evidence for the correctness of the very close relative values for the extracellular

Table V
BODY WATER COMPARTMENTS AND TOTAL EXCHANGEABLE
ELECTROLYTES IN ADULTS

| Sex | Values related to body weight with standard error of the mean | | | | |
|---------|---|---------------------------------|---------------------------------|------------|--------------------------------|
| | ECW
(%) | Cl ₂
(m equiv/kg) | Na ₂
(m equiv/kg) | ICW
(%) | K ₂
(m equiv/kg) |
| Males | 23.4 | 29.3 | 39.5 | 30.9 | 48.0 |
| | ±0.64 | ±0.71 | ±1.06 | ±0.89 | ±1.38 |
| Females | 22.7 | 28.6 | 38.3 | 25.9 | 39.4 |
| | ±0.54 | ±0.92 | ±1.09 | ±0.96 | ±1.10 |

water in the two sexes. The relative values for the total exchangeable potassium which was determined independently of the intracellular water demonstrate a pattern very similar to the findings of the intracellular water. In both measurements the females have a relative value about 20 per cent below the males. As 97 per cent of the total exchangeable potassium must be within the cells this finding can be taken as evidence for the correctness of the measurements of the intracellular water. It is worth mentioning that a calculation of the average intracellular potassium concentration in the two sexes results in very similar values: 152 m equiv per litre intracellular water in the males and 149 m equiv per litre intracellular water in the females, and thus indicates that no difference in cellular composition exists in the two sexes.

and from 25.9 per cent to 22.4 per cent in females. The differences mentioned are not statistically significant except for the decrease in intracellular water in males ($0.01 > P > 0.001$).

The tendency to a decrease in the relative values for total body water found in both sexes is mostly due to a decrease in intracellular water. From an unpublished study of Dr. N. W. Shock (1957) in which the antipyrine space and the thiocyanate space were measured in a larger group of males, the following data are of interest. A comparison of 23 subjects

Table VI
BODY WATER COMPARTMENTS IN YOUNGER AND IN OLDER ADULTS
RELATIVE VALUES

| Sex
(Number) | Age | Height
kg | Water compartments in per cent of body
weight with standard error of the mean | | |
|-----------------|-------|--------------|--|--------------------|--------------------|
| | | | TBIW | ECW | ICW |
| Males
(10) | 23-31 | 72.5 | 54.3
± 1.33 | 23.4
± 0.64 | 30.9
± 0.89 |
| Males
(7) | 71-81 | 63.1 | 50.8
± 1.50 | 25.4
± 1.36 | 25.4
± 0.58 |
| Females
(10) | 23-31 | 59.3 | 48.6
± 1.47 | 22.7
± 0.54 | 25.9
± 0.96 |
| Females
(7) | 61-74 | 63.0 | 43.1
± 1.32 | 21.4
± 0.41 | 22.1
± 0.97 |

aged 40-49 and 32 subjects aged 70-79 showed that the values for total body water related to body weight decreased from 54.8 per cent to 50.9 per cent, and those for the calculated intracellular water decreased from 30.5 per cent to 25.1 per cent. The extracellular water changed from 24.3 per cent to 25.8 per cent only. The same pattern of a slight decrease in total body water and in intracellular water related to body weight was seen in a male series studied by Olbrich and Woodford Williams (1956). Sagild's findings of a decrease in total exchangeable potassium in the old age groups of both sexes can also be interpreted as evidence of a decrease in the intracellular phase related to body weight (Sagild 1956).

When the body water compartments are related to total body water as a standard of reference another sex difference appears. In males the extracellular water accounts for 43 per cent of total body water and in females for 47 per cent, whereas the intracellular water amounts to 57 per cent of total body water in the males and 53 per cent in the females. The difference between these ratios is statistically significant ($P < 0.001$). This difference in the distribution of the total body water between the extracellular and intracellular compartments can be explained as the result of a higher development of tissues rich in intracellular material and relatively poor in extracellular phase, such as muscle tissue, in the males.

In conclusion the sex difference in body composition is outlined as a higher relative content of total body water, a higher relative content of intracellular water and a lower relative amount of total body solids and especially of body fat, in males than in females. The total body water is distributed with a lower extracellular fraction and a higher intracellular fraction in males than in females.

Ageing

Our experiences in the old age group are based upon the investigations carried out in seven apparently normal males with an average age of 75 years and seven apparently normal females with an average age of 68 years. This group was studied in Dr. Francis Moore's laboratory (Parker, Olesen and Moore, 1958). The methods used were the same as those applied to the younger adults.

The essential findings in the old age group are presented in Table VI.

A comparison between younger and older adults reveals the following findings: total body water decreases from 54.3 per cent to 50.8 per cent in males and from 48.6 per cent to 43.1 per cent in females. The extracellular water rises slightly in males and decreases slightly in females. The intracellular water decreases from 30.9 per cent to 25.4 per cent in males

and from 25.9 per cent to 22.4 per cent in females. The differences mentioned are not statistically significant except for the decrease in intracellular water in males ($0.01 > P > 0.001$).

There is a tendency to a decrease in the relative values for total

Shock (1957), in which the antipyrine space and the cyanate space were measured in a larger group of males, the following data are of interest. A comparison of 23 subjects

Table VI
BODY WATER COMPARTMENTS IN YOUNGER AND IN OLDER ADULTS
RELATIVE VALUES

| Sex
(Number) | Age | Weight
kg | Water compartments in per cent of body
weight with standard error of the mean | | |
|-----------------|-------|--------------|--|--------------------|--------------------|
| | | | TBW | ECW | ICW |
| Males
(10) | 23-51 | 72.5 | 54.3
± 1.75 | 23.4
± 0.61 | 30.9
± 0.89 |
| Males
(7) | 71-81 | 69.1 | 50.8
± 1.55 | 25.4
± 1.36 | 25.1
± 0.58 |
| Females
(10) | 23-51 | 59.3 | 48.6
± 1.47 | 23.7
± 0.54 | 25.0
± 0.96 |
| Females
(7) | 61-74 | 63.0 | 43.4
± 1.32 | 21.4
± 0.45 | 22.4
± 0.97 |

aged 40-49 and 32 subjects aged 70-79 showed that the values for total body water related to body weight decreased from 54.3 per cent to 50.9 per cent, and those for the calculated intracellular water decreased from 30.5 per cent to 25.1 per cent. The extracellular water changed from 24.3 per cent to 25.8 per cent only. The same pattern of a slight decrease in total body water and in intracellular water related to body weight was seen in a male series studied by Olbrich and Woodford-Williams (1956). Sagild's findings of a decrease in total exchangeable potassium in the old age groups of both sexes can also be interpreted as evidence of a decrease in the intracellular phase related to body weight (Sagild, 1956).

From the uniform tendencies in these materials it seems reasonable to conclude that the slight decrease in total body water and in intracellular water related to body weight reflects real alterations in the body composition with advancing age. With the decrease in the relative value for total body water there is a relative increase in total body solids. As the intracellular phase shows a relative decrease the increase in total body solids must be assumed to be caused by a relative increase in non cellular solids, most probably body fat.

The alterations in the extracellular water related to body weight are not quite uniform and the changes are small. It is of interest that extracellular water expressed as per cent of total body water in both sexes shows a rise from younger to older subjects, in the males from 43 per cent to 50 per cent, in the females from 47 per cent to 49 per cent. This tendency is also seen in Shock's and in Olbrich and Woodford Williams series and indicates an altered relationship between the extracellular and intracellular water.

In conclusion the alterations in body composition in the old age group as compared to younger adults were rather small. A tendency to a relative decrease in total body water and in intracellular water and a relative increase in total body solids, most probably body fat, was found. The extracellular water stayed essentially the same in values related to body weight, but demonstrated a tendency to increase in per cent of total body water.

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DISCUSSION

Hingerty Are these differences in the intracellular water related to the proportion of functional muscular tissue? If so, the

fat
 reg

Olesen It appears from Dr. Ims Hansen's material that chemical maturity occurs about the age of twelve months.

Widdison Have you made any calculations of the body fat at different ages?

Olesen I have tried to compare the different groups and it seems that there is a relative increase in body fat throughout childhood. It is a slight one but it does exist if we accept that all the non-cellular solid changes are changes in body fat. This calculation is quite apart from possible changes in body minerals and I do not know to what extent these would interfere.

Borst Is there any relationship between the creatinine output and the intracellular fluid?

Olesen I have not seen any of the material of determination of intracellular fluid (Cossa *et al.*) but I have found that there was a relationship between creatinine excretion and the amount of total exchangeable potassium. This has not been studied in this particular series.

Heller How far is it justifiable to take mean figures from ten young adult females without considering the role of the menstrual cycle? Have you had enough cases to pay attention to this point?

Olesen No, but it would appear from what Dr. Swyer mentioned yesterday that it would not mean very much, as the latest view is that these body weight changes are randomly distributed throughout the menstrual cycle.

Shock It seems to me that we have two possible interpretations of this age reduction in intracellular water. The interpretation I favour is that the reduction in total intracellular water is a reflection of the loss of functional cells or the loss of protoplasm rather than a change in the water concentration of the remaining protoplasm. Have we any other evidence that would make one interpretation more probable than the other?

Dalson I think that is a very sound point, because a cell can change in size without there being a change in the relative value of the water or solid contents of the organism. Is there any change in the histological appearance of old tissue that would indicate whether the cells had become smaller or larger?

for the age reduction in basal metabolism in terms of cellular surface area and metabolic rate per unit of body weight.

surface area

Scribner Total exchangeable potassium might possibly be a good parameter for this measurement of protoplasm.

interesting study (to be
in either body

for instance, to the blood volume,

people professionally get the
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THE EFFECT OF VARIABLE PROTEIN AND MINERAL INTAKE UPON THE BODY COMPOSITION OF THE GROWING ANIMAL *

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THE quantities of various nutritive substances in the growing body at any given point represent the metabolic integration of the daily additions to the body from the diet from the time of conception. Measurement of the rate or quantity of addition may or may not measure the nutritional requirement for a given substance. Whether it does or not will depend upon the requirement for synthesis and metabolic transformation and upon the possibility of the body being able to store the substance. Thus, the day-by-day accretion of fat or glycogen cannot measure a requirement but the accretion of protein and mineral may do so, once any capacity for storage is exceeded. Information concerning requirements for growth is usually obtained by measurements of external balance for variable periods of time. The information acquired concerning the requirements for growth and the composition of growth by this method is often strangely contradictory and always incomplete. Much of the data so obtained indicate that extensive storage of dietary components occurs, or that the composition of the body tissues is variable and dependent upon quantity and quality of the intake.

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That body tissues can vary significantly in composition except under extreme conditions is difficult to reconcile with present-day knowledge of tissue composition

The experiments to be described here were undertaken in an attempt to characterize the effects of high and low mineral and protein intakes, in various combinations, upon the body composition of the growing albino rat as determined by direct whole body analysis. Previous work using this method of approach has been concerned with single constituents and not with the interrelationships of all of the components. The data indicate little variability in composition for the collective soft tissues of the body. The only intake-dependent relationship that seems of significance is in the relative proportions of skeleton to soft tissues

Experimental Methods

A Animals and Diets

Male weanling Sprague Dawley strain rats were used in all feeding experiments. Two groups of animals were used to measure food consumption on the high and low protein diets. In these experiments spill proof feeding tunnels were used, and the animals caged singly. The remaining groups of animals were housed in units of four in steel wire cages with open mesh bottoms. Continuous access to unlimited quantities of food in open containers was allowed. Distilled water was similarly offered from dropping bottles. All groups of animals were allowed to grow for a period of 20-25 days. This period of time was chosen as it allowed approximate doubling of weight for the most slowly growing groups.

The experimental diets were compounded using powdered fat free cow's milk (Starlac, The Borden Company), electrolyte and vitamin free casein (Nutritional Biochemicals Corporation, Cleveland) dextrose a fat mixture composed of equal parts of corn oil (Mazola Corn Oil, Corn Products Refining Co., Argo, Illinois) and hydrogenated vegetable oil (Crisco, Proctor and Gamble, Cincinnati, Ohio), and a salt

mixture (NaHCO_3 , 7.4 g, KCl , 12.0 g, CaCO_3 , 12.0 g (NH_4), HPO_4 , 14.9 g, MgSO_4 , 2.5 g KI , 0.001 g) to produce the compositions shown in Table I. The salt mixture was compounded to imitate the ion ratios found in fat free cow's milk. Ferrous sulphate, 2.0 g copper sulphate 0.22 g and aureomycin 0.25 g per kg of diet were incorporated in the mixtures. A vitamin mixture (Vitamin Diet Fortification, Nutritional Biochemicals Corporation) in quantities calculated to make all diets equal in this respect was added to the mixtures.

Table I
ANALYSIS OF DIETS

| Diet | Protein | g/100 g Diet | | g/100 g Diet | | Na | mmole/100 g Diet | | P |
|----------|---------|--------------|--------------|--------------|--------|-------|------------------|------|------|
| | | Fat | Carbohydrate | Fish | Other* | | K | Cl | Ca |
| HPIH | 23.4 | 30.0 | 35.5 | 6.02 | 5.1 | 16.00 | 32.4 | 23.3 | 21.1 |
| HIIF | 23.4 | 30.0 | 35.5 | 1.08 | 5.1 | 8.04 | 16.6 | 14.5 | 11.8 |
| LPHE | 12.0 | 32.0 | 50.5 | 6.02 | 2.4 | 16.00 | 32.4 | 23.4 | 21.1 |
| LPIE | 12.0 | 32.0 | 50.5 | 3.09 | 2.4 | 8.04 | 16.6 | 14.5 | 11.8 |
| Friskies | 26.8 | 6.5 | 51.4 | 11.00 | 3.7 | 15.10 | 15.3 | 13.0 | 84.0 |

* Moisture + Fibre (calculated by difference)

Prior to the beginning of the feeding experiments all animals had been weaned to a commercially produced small animal feed (Friskies The Carnation Milk Company) known to produce excellent growth, general health and reproduction in the albino rat. Preliminary feeding trials with the high protein experimental diets in comparison with the Friskie diet indicated equal effectiveness as measured by weight gain, general appearance, activity, gentleness and lack of morbidity.

Eight groups of animals were studied, namely:

- 1 Weanling group (WEAN) 70-80 g rats weaned to Friskies
- 2 High Protein-High Electrolyte (HPIH) see Table I
- 3 High Protein-Low Electrolyte (HIIF) see Table I
- 4 Low Protein-High Electrolyte (LPHE) see Table I
- 5 Low Protein-Low Electrolyte (LPIE) see Table I

- 6 Rats fed Fishies by way of control See Table I for composition of this ration
- 7 A high protein, high electrolyte group fed to measure food consumption
- 8 A similar group to No 7 but fed the low protein, low electrolyte diet

At the end of the allotted period of growth (20-25 days) the animals were etherized and 2 ml of blood removed for analysis either by heart puncture or tail incision Killing was accomplished by further ether exposure The dead weight was obtained and the abdominal cavity, thorax and skull opened with heavy shears* The whole body was then dried in an oven at 85°-95° C until a constant weight was reached (4-5 days) During the drying process, the carcass was further broken up with heavy shears The disintegrated carcass was extracted repeatedly with a cold mixture of equal parts ethyl and petroleum ether and re dried to constant weight The dried extracted carcass was then homogenized in a Waring Blender with 5 volumes of anhydrous acetone and the solvent evaporated off and the material re dried This process produces a fine homogeneous powder suitable for quantitative analysis The powder was stored in a desiccator

B Chemical Methods

Water Calculated from weight loss after desiccation

Fat During the course of the analytical work, the fat extraction method used as applied to tissues by Hastings and Fichelberger (1937) was examined for completeness of fat extraction when applied to whole carcass Powdered carcass was exhaustively extracted in the Soxhlet apparatus serially using ether alcohol and chloroform This process increased the degree of fat extraction to the extent of 1.5-4 g per animal Analysis of the material subjected to such extraction

* Intestinal contents were not removed

indicated that its nitrogen content multiplied by 6.25 plus the weight of its ash very closely approximated 100 per cent of the material. Consequently, fat has been calculated in all of the data by the relation $\text{Fat} = \text{dead weight} - \text{water weight} - (\text{nitrogen} \times 6.25 + \text{ash weight})$. All of the constituents shown in Table II have been calculated as g, m mole or m equiv per 100 g of protein plus ash (i.e. fat free dry solids).

Ash A sample of carcass powder was weighed after incineration at 600° in platinum.

Nitrogen Determined by macro Kjeldahl analysis using selenium as a catalyst.

Chloride A micro modification of the method of Iowry and Hastings (1942) was used with cold nitric acid filtrates. Samples of the homogenized powder were also analysed polarographically for chloride, using sulphuric acid filtrates with excellent agreement between the two methods.

Sodium, Potassium and Calcium These were determined on the ash after separation of calcium using methods previously described (Bergstrom and Wallace, 1954).

Magnesium Determinations were done on the ash using the method of Fister (1950).

Phosphorus This was determined on the ash by the method of Fiske and Subbarow (1925).

All electrolyte and nitrogen analyses were in duplicate.

Results

The analytical data obtained in the experiments are shown in Table II. For comparative purposes the whole body analyses on the albino rat of Iight and co workers (1934) and of Cheek and West (1956) are included. Also shown are the average data of Widdowson and Spray (1951*B*) for six normal human newborn babies and the data for single whole adult human bodies of Widdowson, McCance and Spray (1951*A*) Forbes, Cooper and Mitchell (1953) and Mitchell and co workers (1945). The data for water, protein and ash have been calculated per kilogram of fat free body weight. The water and electrolytes are also shown using as a reference standard

| Group | Mean | SE | HPLE | LPHE | LPLE | RATS | Protein | 1951B | 1951A | 1950 |
|--|----------------|----------------|-----------------|----------------|-----------------|------|----------------|---------------|----------------|----------------|
| No. of Animals | 10 | 8 | 12 | 12 | 8 | | | | | |
| Body Wt. g. | 71.4
±3.39 | 170.6
±7.18 | 371.6
±11.4 | 111.9
±8.95 | 121.8
±7.1 | | 165.4
±8.92 | 3500.0
(4) | 45.0 kg
(1) | 53.0 kg
(1) |
| Fat Free (F F) Body Wt. (g) | 64.9
±3.18 | 151.8
±7.23 | 149.7
±10.05 | 97.7
±7.15 | 102.9
±12.37 | | 151.9
±9.04 | 2930.0
(4) | 34.4 kg
(1) | 42.8 kg
(1) |
| Fat Free (F F) Body Wt. (g) | 95.0
±0.68 | 62.0
±2.39 | 77.0
±0.78 | 77.0
±0.72 | 55.0
±1.95 | | 706.0
±0.49 | 821.0
(4) | 732.0
(4) | 604.0
(4) |
| H ₂ O g/kg F F Body Wt. (g) | 170.7
±0.00 | 202.2
±0.3 | 194.3
±7.21 | 185.5
±7.62 | 207.0
±15.4 | | 224.5
±5.2 | 203.4
(4) | 102.0
(4) | 235.3
(4) |
| Protein g/kg F F Body Wt. (g) | 34.6
±1.11 | 35.2
±5.8 | 31.1
±0.88 | 40.9
±3.0 | 40.9
±4.8 | | 41.0
±0.85 | 31.2
(4) | 75.8
(4) | 68.6
(4) |
| Ash g/kg F F Body Wt. (g) | 157.0
±15.8 | 323.0
±42.4 | 344.0
±14.6 | 342.0
±15.0 | 312.0
±31.5 | | 328.0
±0.87 | 458.0
(4) | 273.5
(4) | 220.0
(4) |
| H ₂ O/100 g Prot + Ash | 56.2
±0.68 | 20.0
±1.22 | 22.2
±0.80 | 24.1
±1.72 | 24.1
±1.56 | | 24.6
±0.17 | 21.4
(4) | 55.0
(4) | 48.2
(4) |
| Ns m-equiv/100 g Prot + Ash | 35.0
±0.69 | 30.0
±1.21 | 35.0
±1.30 | 34.9
±1.10 | 31.4
±0.61 | | 33.7
±0.07 | 20.8
(4) | 28.4
(4) | 36.5
(4) |
| K m-equiv/100 g Prot + Ash | 215.0
±11.5 | 109.0
±20.5 | 107.0
±9.5 | 252.0
±21.0 | 222.0
±19.8 | | 238.0
±7.6 | 215.0
(4) | 270.0
(4) | 300.0
(4) |
| Ca m-equiv/100 g Prot + Ash | 15.1
±0.65 | 11.1
±0.3 | 11.0
±0.82 | 14.0
±0.82 | 12.8
±0.95 | | 14.1
±1.49 | 9.8
(1) | 11.7
(4) | 12.2
(4) |
| Mg m-equiv/100 g Prot + Ash | 21.5
±0.61 | 16.6
±0.50 | 18.2
±0.70 | 18.5
±0.90 | 18.9
±1.23 | | 17.6
±1.05 | 15.0
(1) | 15.0
(4) | 15.0
(4) |
| Cl m-equiv/100 g Prot + Ash | 95.0
±2.49 | 82.0
±5.9 | 77.7
±2.05 | 96.3
±7.72 | 92.9
±3.89 | | 95.5
±4.1 | 95.5
(1) | 98.0
(4) | 124.2
(4) |
| P m-equiv/100 g Prot + Ash | 143.8
±3.03 | 143.7
±2.49 | 143.4
±5.08 | 146.0
±3.26 | 146.0
±4.7 | | 133.7
±4.7 | 145.0
(3) | 145.0
(4) | 145.0
(4) |
| Na Serum m-equiv/l | 6.6
±0.73 | 5.3
±0.51 | 5.3
±0.42 | 6.2
±0.59 | 6.8
±0.57 | | 6.11
±0.57 | 6.11
(3) | 6.11
(4) | 6.11
(4) |
| K Serum m-equiv/l | 97.2
±2.39 | 104.1
±2.42 | 104.5
±2.71 | 99.8
±3.08 | 102.2
±3.31 | | 102.2
±3.31 | 110.0
(3) | 110.0
(4) | 110.0
(4) |
| Cl Serum m-equiv/l | 5.61
±0.18 | 6.14
±0.22 | 6.14
±0.28 | 5.09
±0.34 | 6.39
±0.45 | | 6.39
±0.45 | 6.39
(1) | 6.39
(4) | 6.39
(4) |
| Serum Prot g/l | — | — | — | — | — | | — | — | — | — |

(2) Derived from regression equations.
(4) No measure of variation available

See original data for min. and max values.
(1) See original data for min. and max values.
(2) Mean data only 70-410 g animals.
(3) Calculated as ash plus protein plus water.
(4) Data of Check and of Widdowson calculated on basis of fat free dry solids. All other whole body data calculated as m-equiv, in mole, or g per 100 g protein plus ash (see text).

100 g of protein plus ash. This is equivalent to the commonly used reference standard of fat free dry tissue (*vide supra*)

Fig 1 graphically presents the currently obtained data in terms of grams of ash, protein and water per kilogram of fat free body. The grams of fat per kilogram of fat free body are shown to the right of the columns. It is evident that the compositions of the fat free bodies are essentially similar. The relative proportions of water, ash and protein have not been greatly modified by variation of the diet producing the growth

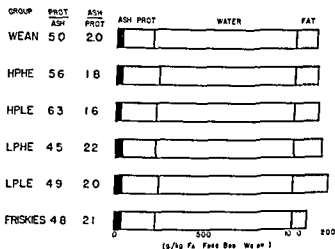


FIG 1 Ash, protein and water content calculated per kilogram of body weight for the six groups. Fat per kilogram of fat free body is shown at the right

increment. Only if body fat were included would gross variation occur. The young animals (WEAN) are relatively low in ash and protein and high in water. With growth the bodies acquired relatively more ash and protein than they did water. The fat contents of the animals on the low protein diets are significantly higher than they are on the high protein.

In Fig 2 the absolute values for total fat free body weight, water, protein and ash for the five groups are shown as contrasted against the Friskie group as an arbitrary reference

standard of growth. The high protein groups are very closely equivalent in weight, protein and water content to the standard. The two low protein groups reach two thirds of the high protein groups with regard to weight, water and protein. The degree of mineral accretion in the high protein animals is significantly different, the high electrolyte group accreting

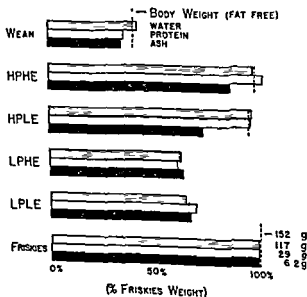


FIG. 2. Absolute composition of body weight (fat free) of various groups.

much more than the low, but less than the Friskies group.

It is noted that the amount of ash is not significantly different.

The high protein animals show a greater relative and absolute accretion of protein than do the low

protein, high electrolyte group. This is significant at the 1 per cent level.

The protein to ash ratios shown in Fig. 1 and evident in Fig. 2 indicate the main significance for body composition resulting from diets of variable protein and electrolyte content. The high-protein-fed animals have more protein in relation to

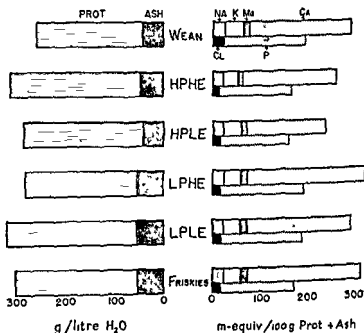


FIG. 1. — Protein and electrolyte levels in the diet of the ash and protein groups. On the left, the levels of protein and ash in the diet. On the right, the levels of the various electrolytes in the diet.

ash than do the low-protein-fed animals. Since bone contributes 90 per cent of the ash, the ratios represent the soft tissue to bone proportions in a very general yet valid way. It seems evident that only on a high protein intake can the growing body lay down maximal bony tissue. In the Friskie group where the ash of the intake is very high and composed chiefly of calcium salts, an even greater accumulation of ash

occurs at the relative expense of soft tissue. Where this relationship stops is not answered by the present data.

tion of ash and protein in the body water and the nature of the composition of the ash are shown in Fig 3. It is evident, as has been noted, that only in the weanlings and in the low protein high electrolyte group does a significantly different amount of protein per unit of water appear.

All of the experimental data for individual constituents of the body have been calculated using four reference parameters: i.e. grams or m mole per whole body, per kilogram of fat free whole body, per kilogram of water and per 100 g of protein plus ash (fat free dry tissue). All of these calculated individual values have been compared among the four groups. The following statements can be made:

I The Effects on the Protein Content of the Body

A By Protein Intake

Only in those animals on the high electrolyte diets did increased protein intake result in increased protein content of the body on any of the enumerated bases.

B By Electrolyte Intake

In the animals on the high protein intakes, the electrolyte effect was variable depending upon the reference base used for calculation. In the low protein fed animals a high electrolyte intake reduced the protein content of the body calculated on any basis.

II The Effects on the Mineral Content of the Body.

A By Protein Intake

On any basis of calculation, other than absolute body size, the bodies of the animals fed a low protein intake, whether with high or low electrolyte, contained more ash, calcium,

magnesium, sodium, chloride and phosphorus than those fed a high protein intake.

B. By Electrolyte Intake.

The high electrolyte diets led to increased calcium and decreased chloride in all groups calculated on any basis.

In the high protein groups the high electrolyte intakes also resulted in more ash and less potassium when calculated on any basis

In Table II the serum concentrations of sodium, potassium, chloride and total protein are shown for the four experimental groups. The only consistent significant difference is for the concentration of total serum protein. Serum protein concentrations are higher in the high-protein-fed groups. The lower protein concentration may indicate protein deficiency in the low protein group and other evidence for such deficiency is given below. The validity of serum protein concentrations as a reliable index of protein malnutrition can be questioned. In this connexion it is of interest that the serum protein concentration of the breastfed infant is lower than that of the infant fed cow's milk (Tudvad, Birch-Andersen and Marmer, 1957).

Animals in experimental groups No. 7 and No. 8 were fed in such a manner as to allow accurate measurement of food intake. The high protein group consumed 8.2 g of ration per animal per day in contrast to 9.3 g per day for the low protein group. The mean weights for the two groups at the end of 23 days were 174 and 155 g respectively. Calculation of the caloric values for the whole bodies of these animals shows that the high protein group contained 292 calories per average animal (1,710 calories per kg) and the low protein group 263 calories per average animal (2,085 calories per kg). Calculation of the calories utilized for physiological activity indicates that the low protein group expended 175 calories more per animal for the period of observation than did the high protein group. Increased spontaneous activity was clearly evident in the low protein groups during the period of

EFFECT OF VARIABLE INTAKE ON BODY COMPOSITION 127
 observation. Increased spontaneous activity with nutritional
 deficiency has been previously noted (Forbes et al, 1935;
 Bevan et al, 1950)

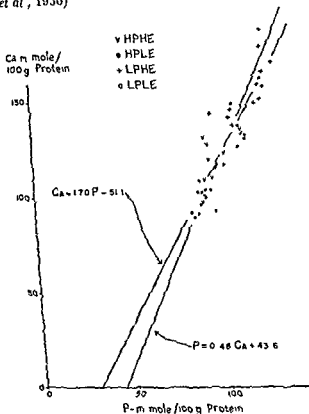


FIG. 4 Relationships of calcium and phosphorus to protein in the experimental groups. For description of method of construction, see text

The data in Fig. 4 represent the calcium/phosphorus relationship in the four principal experimental groups. On the assumption that the protein content is a basic unit of structure, the values are compared in relation to protein. One advantage of this formulation is that the intercept of the

regression line on the X axis defines the amount of phosphorus present in 100 g of calcium free protein. This value should reflect primarily the phosphorus content of muscle tissue. From the statistical analysis of the calcium phosphorus relationship, a correlation coefficient of +0.90 was derived. Further, by the analysis of variance technique, it has been determined that the regression curve is a straight line, described by the equations $\text{calcium} = 1.70 \text{ phosphorus} - 51.1$ and $\text{phosphorus} = 0.48 \text{ calcium} + 43.6$ when both are expressed as m mole/100 g protein, and $\text{calcium} = 2.19 \text{ phosphorus} - 2.04$ and $\text{phosphorus} = 0.37 \text{ calcium} + 1.35$ when both calcium and phosphorus are expressed as g/100 g protein. The X intercept is between 30.3 and 43.6 m mole phosphorus/100 g protein or between 0.93 and 1.35 g phosphorus/100 g protein. It is of interest that the calcium/phosphorus ratios of the four groups of rats studied by Light and co workers (1934) and the infants analysed by Widdowson and Spray (1951) also lie on this regression line when their values are calculated in this manner. This indicates that the changes in phosphorus content of the various groups are related to the changes in calcium and to the total amount of protein present. The phosphorus concentration is constant in the "soft tissue" (calcium free protein), and the phosphorus has a constant ratio to the calcium in the "skeleton" (calcium containing tissue).

It is also apparent from the figure that the calcium to protein ratio is highest in the low protein high electrolyte fed animals and lowest in the high protein low electrolyte group.

Discussion

The present data, like the very similar data of Widdowson and McCance (1957) and Stanier (1957), indicate no real evidence for storage or depletion of protein with varying intake. The basis for such a judgment is made by examination of data calculated using either a kilogram of fat free whole body or 100 g of fat free dry solids as a standard of reference.

The rationale for the use of the latter standard has been discussed in detail elsewhere (Cotlove *et al*, 1951). While such a reference point is essential for evaluation of acute shifts of water and electrolytes in tissues, it may not be equally applicable where the growth of a complex of tissues is involved. In this latter situation it is essential that the relative gain or loss of a substance in question be examined in regard to a number of reference standards, as has been done here (see Results). When the change in any constituent is consistent in direction regardless of the reference basis, it is probably a real one, as has been noted above. However, when the change is in one direction on one basis and in the opposite on another, the question of gain or loss is difficult to assess. An example of this from the current data is found in the change in potassium content with change in protein intake in the animals on the low electrolyte diets. The high protein fed animals were larger and contained more potassium on an absolute basis. When calculated per kilogram of fat free body the potassium concentrations were equal, but on a litre of water basis the potassium was greater in the low protein group. Again, referring this ion to fat free dry solids, the high protein fed animals would seem to have the highest content. For the purposes of nutritional evaluation, it is valid to calculate constituents as per unit of whole body inclusive of fat. When this is done, an even greater number of permutations and combinations can be found with regard to relative contents of all substances. Until more is known concerning the distribution function and relationships of protein and electrolytes in tissues it would seem advisable to emphasize only those changes which are relatively consistent.

When the present data are considered on this basis, the composition of the body with regard to water, protein and ash is the same despite variation of the components of the intake. The whole body may be smaller or larger as limited by the availability of certain crucial nutrients but its relative composition remains unchanged. Only the relative size of the skeletal mass in relation to soft tissue seems to be significantly

susceptible to some variation by variation of dietary intake. Even in relation to skeletal tissue the possibility of variable composition is limited by another parameter, i.e. protein. Thus, the composition of the body achieves an independence from the environment, an independence that would seem essential in a living system where metabolic function is carried on by protein with its critical requirement for constancy of water and ionic concentration.

The concept that the whole body or the cells of the body may be enriched or depleted of their various chemical constituents by variation of the dietary intake is widely supported in the nutritional literature. By examination of retentions during balance observations on growing infants, it may be concluded that the higher the intake of a substance, the greater will be its final concentration in the body per unit of weight (Rominger and Meyer, 1927, Swanson and Job, 1933, Stearns, 1939).

Correlation of weight gains of premature infants with the protein and ash content of the milk fed has shown high positive correlation with the increasing ash content (Kagan *et al*, 1955). Conversely, possible support for the concept of variable body composition stems from nitrogen losses after trauma. Both animals and men maintained on low protein intakes lose less nitrogen after trauma than do those with prior optimal intakes (Munro and Cuthbertson 1943, Cuthbertson 1948). Holmes, Jones and Stanier (1954) found evidence indicating that men shifted from very low protein intakes to optimal intakes retained nitrogen far in excess of that calculated from weight gain and external losses. The use of the terms 'depletion' and 'deficiency' bears tacit evidence for the belief in the concept of cellular impoverishment during nutritional deprivation. The majority of the evidence for the concept of variable storage of protein and minerals and loss during deprivation stems from the technically hazardous techniques involving measurement of external balances. The possibility of low correlation between apparent retentions or losses and changes in body weight has not been

commonly realized. The shortcomings of the balance method are functions of such items as the effects of variable caloric intake, quality and quantity of protein intake and mineral ratios on the fat content of the body, the distribution of body water and the relative size of body components such as skeleton and muscle. These problems have been most completely explored in relation to evaluation of the problem of protein adequacy (Mitchell, 1944, Allison, 1954, Calloway and Spector, 1953, Spector and Calloway, 1953). It is also little appreciated that systematic errors occur in the calculation of apparent retentions that are cumulative in a positive direction, the magnitude of the cumulative error being in direct proportion to the magnitude of the intake. This makes difficult the comparison of retentions at variable intakes. The relevance of this criticism with regard to calcium retentions has been discussed by Mitchell and Curzon (1939) and by Mitchell and co workers (1945).

Examination of the composition of growth increments by direct body analysis has shown that, once chemical maturity is reached, the composition of the fat free body with regard to protein and ash is nearly constant regardless of any procedures taken to modify weight gain (Moulton, 1923 Moulton

is not a source of calcium (Light et al., 1934)

The concept of variable cellular composition of the body is difficult to reconcile with the knowledge of the composition of tissues. All of the individual tissues of the albino rat have been analysed for their water, protein, fat and mineral content by many investigators. All of these data show a monotonous constancy when calculated on a fat free basis. This occurs despite almost infinite variation in the rations fed to the animals. Unless special experimental conditions are imposed,

imp- 3

comp

et al

• • • • • composition is constant Even

with age the maximum change of water content is no more than 1 per cent and of potassium 5 per cent

Examination of whole body data, with certain salient exceptions, also shows rather remarkable constancy. Fat is probably the only component of the total body that can vary within rather wide limits and still allow reasonable well being to exist. Variation from 10 to 50 per cent can occur without apparent evidence of malfunction. The water content of the fat free body is more closely guarded. Variation of much more than ± 5 per cent from a rather rigid norm results in rapid increments of physiological disability. Moreover, allowable variation of body water is primarily extracellular, cellular water content, within the limits of viability, must be confined to much smaller variations. Since protein is the critical parameter against which water content must be judged, it follows that protein concentration must also be highly critical and susceptible to only minute variation. The consideration applying to water must also hold for the chief extracellular electrolytes, sodium and chloride. Deficit of potassium in the whole body to the extent of approximately 25 per cent does occur, and is replaced by variable gains of total body sodium (Schwartz, Cohen and Wallace, 1953, Cheek and West 1956). The studies of Sherman and Booher (1931) show that the calcium content of the whole body is widely variable in response to variation in the dietary intake. Definition of the optimal body content of this ion is elusive.

In the discussion so far the point of view has been taken that in order to justify the terms *stored protein* or *mineral*, these must exist as physically demonstrable entities comparable to glycogen and fat in the body. It would appear that the essential organic structure of the body cannot be affected in quality by adjustment of the diet. The careful chemical analyses by Luck (1936) of rat liver proteins from animals maintained on varying levels of protein intake indicate that all fractions of the liver proteins have participated equally in any "storage" process. Madden and Whipple (1940) have defined the reserve store of protein as all of the protein

which may be given up by an organ or tissue under uniform conditions without interfering with organ or body functioning. This definition indicates primary physiological significance not anatomical. In this view the primary requirement for furthering understanding would be methods for characterizing and distinguishing physiological depletion. The response to repletion has been used to assess the degree of depletion in such a physiological sense. The work of Madden and Whipple (1910) and Cannon (1934) illustrates the fruitfulness of the method for studying the metabolism of protein under conditions of deficit. Cooke and co workers (1952) and Schwartz, Cohen and Wallace (1955) have applied the technique to experimental potassium deficiency and Hansen (1956) to the potassium deficit in kwashiorkor. The ability to survive in stressful situations provides a further avenue of approach. Haur and Filer (1957) employing the weanling pig growing on diets similar to those used in the present experiments have shown differing abilities of animals growing on different diets to resist water and caloric deprivation. Their data indicate that animals maintained on low protein intakes survive caloric deprivation to a greater degree than do those maintained on high protein intakes. Conversely, the high protein fed animals withstand water deprivation to a greater degree than do their low protein fed companions. Sherman (1916) has correlated calcium intake with life span and reproductive life. A newly opened approach to the problem of characterizing and assessing deficits in a physiological sense is that of distinguishing structural versus enzyme protein in tissues. Potter and Klug (1947) have shown that liver oxalacetate and succinate oxidases are depressed.

• number of other tissue enzymes

Summary and Conclusions

The composition of growth of the albino rat on high protein high electrolyte, on high protein low electrolyte, on low

protein high electrolyte and on low protein low electrolyte diets has been examined. Analysis of the whole body for protein, water, fat, ash, sodium, potassium, chloride, calcium phosphorus and magnesium was performed on animals allowed to double their weaning weights on the enumerated diets.

The animals on the low protein intakes grew significantly less and their bodies contained more fat. The composition of the fat free bodies on a unit basis were all essentially similar despite the variation of the food intake. The principle difference resulting from variation in intake was in the quantity of the skeletal constituents in the various groups. The animals consuming the low protein rations contained more calcium and phosphorus on a unit basis than did the high protein fed animals.

On the high protein intakes accretion of skeletal minerals was dependent upon the level of electrolyte intake, being higher in the high electrolyte fed animals. In the low protein fed animals accretion of skeletal minerals was less affected by the level of electrolyte intake.

Only in the animals on the high electrolyte diets did increased protein intake result in increased protein content of the body.

The significance of the data for nutritional evaluation is discussed.

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DISCUSSION

Widdowson: May I suggest, Prof. Wallace, that you started your experiments far too late. If you had started at 21 "Adolph days" instead of 21 "Wallace days", you might possibly have got different

larly the skeletal muscle, is more rapid in the fast-growing rats.

Wallace How are they different? Are they dilute?

Widdowson The proportion of extracellular fluid in the bodies and muscles of all the rats decreases with development, and the proportion of intracellular constituents, nitrogen and potassium, rises, but the changes take place more quickly in the fast-growing animals, so that they reach chemical maturity at an earlier age

Ann. appl. Biol., 13, 374, and 14, 171) He did fantastic things like suckling mice with rat foster-mothers and getting them up within 21 days to something like 75 per cent of an adult mouse's weight. I went over this again, breaking the changes down week by week (1957. *J.*

to body weight, so naturally the bigger rat ate more and continued to grow faster.

some would get a higher protein and electrolyte intake than others. Analysis of the food or of these samples of eggs or the sheep might be necessary.

repared. If gain of weight per gram of protein consumed is calculated the values are 0.41 g. per g. gain and 0.30 g. per g. gain for the high and low protein diets.

composition of the low protein diet

Wallace: Can you

find out

are the

extremes. Under conditions which do change body composition.

I do not believe that

by changing the pla

more accurately the

by the balance meth

McCauley: What would be the effect of change in diet on electrolytes in the body? Our conclusion at the moment is that it has little effect on the composition of the cell.

Wallace: We can

change the a

but its comp

Heller: On

of the diet

We have rec

plantains, t

After about four weeks there was an increase of 5-7 per cent in total body water, but the interesting thing is that the plasma potassium and plasma

Wallace The calcium in the body is almost entirely skeletal and with this kind of data it is impossible to say just where this calcium is. You have to study the individual tissues.

Fourman Do you think that the increase in bone which you suggested took place is an increase in trabecular bone—so called freely available mobilizable, bone tissue?

Wallace
trabecular
electrolyte
conditions of stress

McCance You began by putting up charts of balances showing that if the diet contained more sodium and potassium, the child absorbed and retained more. Yet you find by experiment that you do not alter the composition of the body. Can you reconcile those observations?

Wallace This is a purely technical matter on which I have strong feelings. In a balance experiment the quantity of food entering the body and the excreta recovered are always slightly less than the measurements indicate. The more refined the technique the smaller this error is. Also, the greater the concentration of a nutriment in the intake the greater will be the error when compared with intakes of lower concentration but of equivalent caloric value. When subtraction is used to calculate the balance these errors accumulate. The errors in doing a balance are not randomly plus or minus as is generally believed, but systematically positive. Much of the arithmetical difficulty arises because one must subtract two quite large numbers to obtain the usually very small balance value. At zero intake the balance method becomes more accurate. Body composition estimates such as can be made from Benedict's and Gamble's fasting data agree with direct analysis data quite well. However, body composition estimates made from balance data

THE EFFECT OF AGE ON THE BODY'S TOLERANCE FOR FASTING, THIRSTING AND FOR OVERLOADING WITH WATER AND CERTAIN ELECTROLYTES *

NATHAN B. TALBOT and ROBERT RICHIE

*Department of Pediatrics Harvard Medical School and the Children's Medical
Service Massachusetts General Hospital Boston*

As is well known, the body is equipped with homeostatic systems designed to maintain water and electrolyte content and concentration values at physiologically optimal levels. The systems accomplish this task largely by equating output with input. While rates of input can be varied widely without overreaching the capacities of the homeostatic systems concerned, nonetheless there are limits beyond which one cannot go without getting into difficulty (Talbot, Crawford and Butler, 1953, Talbot *et al.*, 1955). Thus for each substance there is a *physiological minimum requirement* or *floor*, which is the least intake of the substance in question needed to balance output and hence to prevent deficits where conservation forces are acting maximally. There is also for each substance a *physiological maximum tolerance* or *ceiling* which is defined as the largest amount of the substance that can be taken and eliminated without seriously disturbing body composition. Rates falling between these two parameters may be said to fall within the *physiological* or *safe working range*. When the rate of administration of a substance falls outside this range for an appreciable length of time, body composition deviates from normal and manifestations of disordered homeostasis develop as outlined in Table I.

* This paper is based on work supported by grant A-809 of the National Institute of Arthritis and Metabolic Diseases by grants II-1529 and IITS 5139 of the National Heart Institute, United States Public Health Service and by a grant from the Commonwealth Fund of New York.

The manner in which a limit to homeostatic capacity can be recognized and defined is illustrated in Fig 1 (Talbot *et al*, 1956). Here it can be seen that this patient maintained a normal potassium status, as judged from electrocardiographic T waves and from serum potassium concentration, and remained in potassium balance at rates of intake up to approximately 70 m equiv per m² per day. These rates of

Table I

INDICATIONS THAT INTAKE IS PHYSIOLOGICALLY EXCESSIVE OR INSUFFICIENT
(ADULT VALUES)

| Sub-stance | Too Much | Too Little |
|------------------|---|--|
| H ₂ O | Water intoxication
Serum water >3.8 ml /m osm * | Hypohydration
Serum water <3.4 ml /m-osm * |
| Na | Extracellular oedema
Na _E ↑ > 20% | Extracellular dehydration
Na _E ↓ > 12% |
| K | Weakness I CG
T waves ↑
Serum K >6.5 m equiv /l | Weakness I CG
T waves ↓
K _I ↓ > 20% |
| P | Serum P >6 mg % | Osteomalacia |

Na_E = extracellular sodium

K_I = intracellular potassium

* Corrected for urea.

intake could therefore be considered to be within his safe working range. By contrast higher rates of intake led to a sustained positive balance and to the appearance of elevated T waves and hyperkalaemia which are taken to be signs of potassium intoxication. Accordingly, it may be said that this individual's ceiling of tolerance for potassium was about 70 m equiv per m² per 24 hours a subnormally low value in comparison with a normal ceiling of at least 250 m equiv per m² and in keeping with the fact that he was suffering from marked impairment of renal function.

The same principles have been used in estimating the upper and lower limits of body tolerance for water and certain electrolytes for normal individuals of various ages, depicted in Fig 2. The upper limits shown in this figure are of necessity approximate, being based on the relatively few data available in the literature and the files of our metabolic unit (Talbot *et al*, 1952, Talbot, Crawford and Butler, 1953, Talbot *et al*,

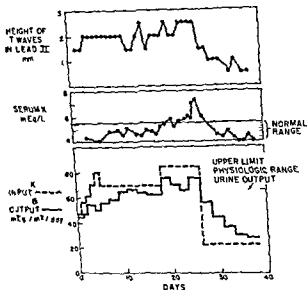


FIG 1 Demonstration of physiological maximum tolerance for potassium in a patient with impaired kidneys. (From Talbot *et al* 1956)

1955, 1956, Talbot, Richie and Crawford, 1958) In all instances, they are intended to represent levels which can be attained by healthy individuals within a day or so and not the uttermost levels which can be attained after extensive prior conditioning. The lower limits include normal growth requirements for infants and children, a factor of relatively small size after the first few months of life. It can be seen that with the exception of young infants, individuals normally

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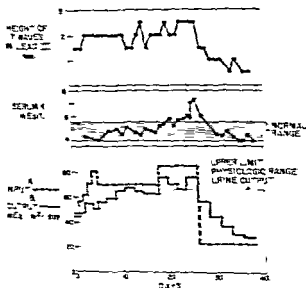


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Na_E = extra-cellular sodium

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which occur during the growth period, in each case average normal values for body composition and content were used (Shohl, 1939, Forbes and Perlev, 1951, Corsa *et al*, 1956, Fris Hansen, 1957) Each substance has been considered separately In dealing with water, sodium and potassium,

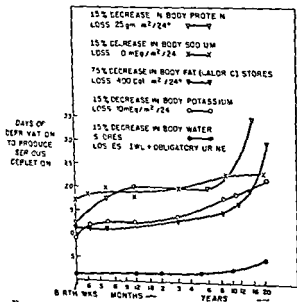


Fig 3. Days of deprivation (ordinate) needed to produce the percentage decrease in body content indicated for each substance in individuals of various ages (abscissa). The rates of loss indicated for each substance approximate to physiological minimum output rates of which some are indicated by the lower boundaries of the physiological tolerance ranges shown in Fig 2

rate of loss was taken as the physiological minimum requirement value indicated in Fig 2. In considering body fat (caloric) stores, energy expenditures were assumed to be at the rate of 1,800 calories per m² per day (Macy, 1942) and to be derived entirely from body fat. Body protein losses were calculated assuming a basal rate of loss amounting to 25 g per m² per day, the minimum value attained by individuals

utilize but a small segment of their homeostatic capacities. In early infancy, the margins of safety are relatively quite narrow, a fact long recognized by those interested in paediatrics.

The clinical significance of these homeostatic parameters

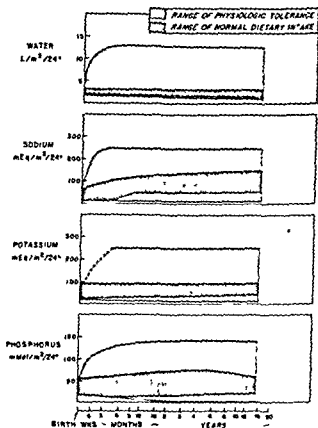


FIG. 2 Estimates of the safe working ranges of intake for individuals of various ages and of the portions of these ranges used by persons taking ordinary diets for age.

may be visualized by considering the length of time needed for individuals of various ages to lose a significant portion of their body stores when totally deprived of water or certain other substances (Fig. 3). In calculating these time values, attention has been given to the changes in body composition

water, ± 7 per cent (Wynn, 1956), potassium, ± 5 per cent (Drescher *et al.*, 1958), total body sodium (euproteinaemic subjects), ± 30 per cent (Leaf, personal communication). In the case of phosphorus the end point chosen was elevation of extracellular inorganic phosphorus concentration to 12 mg

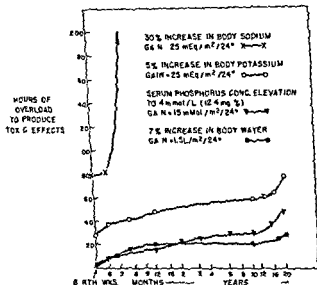


FIG. 4 Hours of overload (ordinate) needed to produce the percentage increase in body content indicated for each substance in individuals of various ages (abscissa). The rate of gain is that which obtains when rate of input exceeds the physiological maximum tolerance levels for adults shown in Fig. 2 by approximately ten per cent.

per cent * Individuals who have surpluses of these degrees are apt to show the signs of intoxication listed in Table I.

As might be expected, Fig. 4 indicates that infants are relatively much more vulnerable to overloading than older children and adults. This is true not only in the relative terms depicted here, but also in absolute terms because the quantity needed to produce intoxication in a small individual

* This assumes no body's capacity for cellular or skeletal storage of surplus inorganic phosphorus—a point on which we have no objective information.

receiving at least 75 grams of carbohydrate per m.² per day (Gamble, 1946-7). It was arbitrarily decided that a 15 per cent decrease in body water, sodium, potassium or protein or a 75 per cent depletion of body fat (calorie) stores constituted a significant and potentially serious loss.

As indicated by the upward trend from left to right of the curves of Fig. 3, infants and children up to three years of age, when deprived of any one of the substances represented, are apt to become depleted two to four times faster than adults. For example, infants will develop as serious a degree of water depletion within one and a half days as adults do in the course of about five days of total thirsting. Likewise, infants deprived of electrolytes or protein or calories may lose an appreciable portion of their body stores of these items after nine to 17 days of deprivation.* By contrast, it takes 20 to 35 days for adults to become similarly depleted under conditions where homeostatic conservation forces are operating efficiently. These observations indicate that in infants who must be maintained by parenteral fluid therapy for more than a few days, special attention should be given to the provision not only of water, carbohydrate and the main extracellular and intracellular electrolytes, but also of maintenance allotments of calories and either preformed protein or amino acids. The same would apply to older children and adults who are depleted or have to be sustained by parenteral fluid therapy for more than a week or ten days.

Fig. 4 deals with the opposite phenomenon of overloading. Here again it has been necessary to make arbitrary decisions concerning the size of the overload and the degree of retention to be considered significant. It was decided to postulate rates of input that were ten per cent in excess of adult physiological maximum tolerance or ceiling values. The end point values for the retentions of toxic degree resulting from these physiologically excessive rates are related to the respective average normal body content values at each age as follows: total body

* The rate of loss would be considerably greater under conditions of zero carbohydrate intake (Gamble, 1946-7).

dextrose, 40 m-equiv. of sodium, 35 m-equiv. of potassium, 40 m-equiv. of chloride, 20 m-equiv. of lactate and 15 m-equiv. of phosphate (Talbot, Crawford and Butler, 1953; Talbot *et al*, 1955). The first set of subjects received their allotment by mouth in an essentially continuous (hourly dose) manner, the

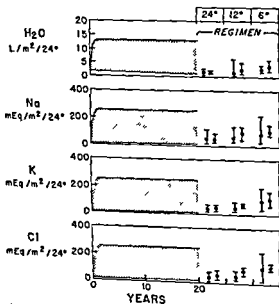


FIG. 6. Relations between rates of output observed for subjects on various regimens.

(Talbot, Neyzi, Bailey and Talbot, 1958)

second set at twice the rate for 12 hours each day and the third set at quadruple the rate for six hours out of every 24. As indicated by the length of the vertical lines at the right of Fig. 6, those on the 24-hour regimen utilized but a small fraction of their physiological ranges of excretory capacity in accomplishing metabolic homeostasis. By contrast, those on

is not very great. The curves indicate that one is apt to become water and phosphorus intoxicated before one becomes potassium or sodium intoxicated. It is interesting that these relations are in keeping with clinical observations on patients with marked limitation of renal function (Talbot *et al*, 1956).

One of the areas where the foregoing considerations appear to have practical implications is with respect to parenteral fluid maintenance therapy. Review of hospital practices

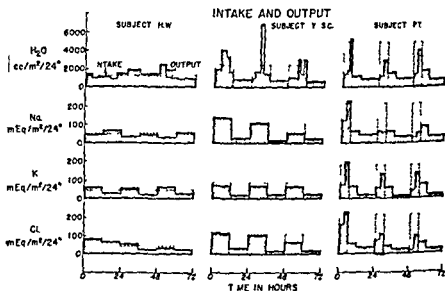


FIG 5 Intake and output of water and electrolytes by normal adult subjects receiving a standard maintenance allotment of multiple electrolyte plus dextrose solution in 4, 12 or 6 hours each day (From Neyzi, Bailey and Talbot 1958)

reveals that some physicians give the total daily fluid, carbohydrate and electrolyte allotment in a slow continuous manner while others administer the total daily dose in a few hours, allowing the patient to fast and thirst for the remainder of the 24 hour period. The data shown in the right hand sections of Fig 5 (Neyzi, Bailey and Talbot, 1958) indicate the ranges of output rate observed on two sets of three normal adults maintained for three days on an ordinary dose (1,200 ml per m² per day) of a solution containing per litre, 50 g of

may encounter in young infants and in patients undergoing the stress of anaesthesia and surgery. As the columns show, the percentage gains to be expected for infants are approximately twice as great as those to be expected for adults. While the gains indicated for adults are borderline as regards

approximate terms the limits of capacity of the body to adjust output of water and certain other substances in accordance with homeostatic needs, and to illustrate the clinical implications of such knowledge.

These thoughts are presented in the hope that they may elicit constructive suggestions concerning these highly significant, yet rather elusive phenomena.

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the 12 hour and especially those on the six-hour regimens used almost fully their normal adult ranges of renal excretory adjustment in the course of each 24 hour period. When the homeostatic adjustments in water and electrolyte excretion exhibited by these adult subjects are viewed with relation to the infant ranges of homeostatic adjustment indicated by the shaded zones of the left-hand sections of Fig. 5, it can be seen

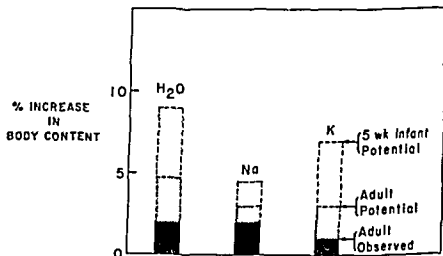


FIG. 7. Percentage increases in body water, sodium and potassium content

that they are considerably greater than those of which such young individuals are capable.

Fig. 7 depicts the percentage increases in body water, sodium and potassium content which would occur during the course of the infusion period if a day's total maintenance allotment of 1,500 ml per m² per 24 hours* were administered in six hours to a patient who was unable to increase rates of urinary output above the physiologically low levels characteristic of fasting and thirsting, a situation which one

* This is an ordinary allotment for infants and children on our Service.

parenterally. It is said that one of the safeguards in oral ingestion of water is the fact that elimination goes on about as fast as absorption.

Talbot: As far as water, sodium and potassium are concerned, it is six one way and half a dozen the other whether they are taken by vein or by

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DISCUSSION

Black. There seems to be some conflict between Dr Talbot, who says that large intakes should produce retention and Prof Wallace who tells us that large intakes produce large arithmetical errors. In this matter I am on Dr Talbot's side, and that is not entirely the emotional reaction of someone who has done a certain amount of balance experiments. I think we have some supporting evidence in that if balance experiments are done on an adult person who has just had an operation and is on a milk intake (in which the errors of measurement should be much the same as those of excreta), there is quite a definite correlation between intake and retention (Davies, H. L. 1, Jepson, R. P. and Illick, D. A. K. (1956) *Clin Sci*, 15, 61).

Bull. What was the nature of the load imposed in the experiments on the tolerance of loading?

Talbot. The rate of intake of the substances in question is increased in a stepwise manner which allows time for compensatory homeostatic adjustment in rate of output to take place. At each step measurements are made to find out whether the body content and/or concentration of the substance is being kept within physiological limits by appropriate adjustments of the rate of output. As rate of input is increased it eventually reaches a point where the body is unable to keep its content and concentration values within normal limits by suitable adjustment of rate of output. This point is considered to be the upper limit of physiological tolerance or physiological ceiling for the substance in question. Rates of input in excess of this ceiling level produce a tendency to abnormal retention. For example in the case of potassium when the rate of input exceeds the physiological ceiling value body potassium content increases above normal levels and hyperkalaemia develops together with signs of potassium intoxication.

McCance. I would like a firm definition of what you mean by tolerance and capacity to eliminate. De Wardener did some experiments in which he took large amounts of water every day for 7 or 14 days and although he did not succumb and appeared to tolerate them perfectly well there were finite changes in his responses, sensitivities etc. (de Wardener

solute ratio of their urine above a few ml per m-osm and whose rate of excretion was not significantly altered by the intake of large amounts of water.

one of zero potassium intake On the other hand, it was thought that a
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and refine them more by detailed definitions of certain
important interrelations

You are correct in your deductions concerning our aims in defining
physiological key variables The present definitions are of necessity ap-
proximate and potentially subject to modification and refinement At
the same time they are proving to be of value as indices of patient status
and as a point of departure for investigation

observed that rats offered gradually increasing quantities of potassium in their diet ate and absorbed the relatively very large quantities needed to produce a lethal degree of potassium intoxication. They did not develop diarrhoea, nor did they vomit, they just became weak and died. Likewise, we have seen a patient with marked limitation in tolerance for potassium due to advanced pan nephritis become fatally intoxicated with potassium as a result of drinking fruit juices.

Adolph The study of tolerances is a very important aspect of the general physiology of regulatory processes. Dr. Talbot, you estimated tolerances in terms of single constituents, but in some of the situations you described such as the intravenous administrations you were concerned with several constituents at a time. Now when there is depletion or excess of more than one constituent at a time the picture is very different with respect to tolerance. For instance there is a great difference between taking pure salt and taking an isotonic solution of salt. I recognize that this work is exploratory and that you are making your estimates in the simplest way possible when you consider one component at a time but eventually I hope we shall have some estimates of tolerance to multiple components.

This consideration of components seems to me to extend also to your studies of composition. Prof. Wallace: If you went to your statisticians still more often would you not get into the study of multiple correlations which would get us further than comparisons made two at a time?

Wallace We have made a number of statistical multiple correlations. It is often difficult to know just what they mean once certain correlations become evident. Our biggest problem has been to have any assurance as to the proper parameter to which to refer growth. Should the reference basis be body weight, fat free weight, protein, ash or water?

Adolph What I want to bring out is that an organism probably has some way of measuring the bodily composition which is very much more complicated than saying for instance that magnesium is the fixed constituent around which all others revolve. I think that without a study of multiple correlations we will never be able to find whether there is a fixity by which homeostasis is guided to a definite volume and concentration to which the organism always returns. I do not know whether any of our methods of representing homeostasis will be so similar to that of the organism that we can predict what it does to get back to its fixity.

I should also like to remark on Dr. Talbot's choice of a key variable. No doubt he has great reservations about the use of this term. What he is trying to do I gather is to out-guess the organism as to what it is using as a measuring stick by which it will return to its original composition or by which it will estimate what has to be done in order to defend itself against disturbances. When we think that an organism is restoring its potassium concentration have we any assurance that that one restoration is a prime objective in the adjustments which are going on?

Talbot We agree with you that most if not all of the variables under consideration are related to each other. For instance it is known that body tolerance for potassium is impaired under conditions of zero sodium intake and that tolerance for sodium is abnormally limited under condi-

(4) Partly due to the interrelationships (2) and (3) kidney function is readily impaired by stress

Thus the high incidence of body fluid disturbances is partly due to the occurrence of disease and partly to relatively inefficient homeostatic defence mechanisms. The latter is well

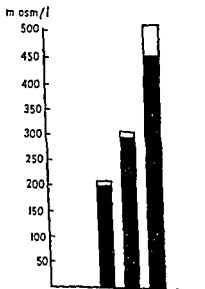


FIG 1 Labilty of osmotic regulation in 10 day-old puppies.

| | |
|----------------|-------------------|
| Left column | salt and protein |
| Central column | free diet |
| Right column | normal |
| | concentrated milk |

illustrated by the observation that diets such as milk evaporated to one-quarter of its original volume, or salt and protein free food bring about great changes in the tonicity of the body fluids (Csapó and Kerpel Fronius, 1933, Kerpel Fronius, 1933). After the first, the osmolarity of the blood plasma in puppies rose to 520 m osm/l, 457 m-osm being accounted for by 'hyperelectrolytaemia', after the second, the electrolytes decreased to 232 m osm/l (Fig 1). There

CLINICAL CONSEQUENCES OF THE WATER AND ELECTROLYTE METABOLISM PECULIAR TO INFANCY

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DISTURBANCES in the volume and composition of the body fluids occur more frequently in infancy than at other ages. Among the reasons for this are

(1) The high incidence of diarrhoea, malnutrition, and certain congenital defects

Diarrhoea is still one of the paediatrician's major concerns, one of its main causes being colon bacilli, pathogenic only for this age group

Owing to their high caloric and protein requirements infants easily succumb to malnutrition, which progresses rapidly. The resulting expansion of the volume of their extra cellular body fluids, sometimes accompanied by asymptomatic hyponatraemia, is a common disturbance of homeostasis in some countries

Congenital defects of the oesophagus, the pylorus, the renal tubules, the adrenals, and the central nervous system may also cause serious disturbances in the body fluids, their discussion is beyond the scope of this paper

(2) Circulation, metabolism and renal excretion are all maintained at high levels relative to the volume of the body fluids

(3) When growth is arrested by disturbances which diminish the utilization of food, a fraction of the intake normally retained is rejected, thus raising the solute load on the kidneys

* In the absence of Prof. Kerpel-Fronius his paper was read for him by Dr. Winifred Young

(4) Partly due to the interrelationships (2) and (3) kidney function is readily impaired by stress

Thus the high incidence of body fluid disturbances is partly due to the occurrence of disease and partly to relatively inefficient homeostatic defence mechanisms. The latter is well

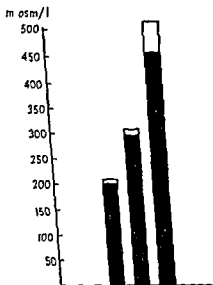


FIG. 1 Lability of osmotic regulation in 10-day-old puppies

| | |
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| Left column | salt and protein |
| | free diet |
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illustrated by the observation that diets such as milk evaporated to one quarter of its original volume, or salt- and protein-free food, bring about great changes in the tonicity of the body fluids (Csapó and Kerpel-Fronius, 1933, Kerpel-Fronius, 1933). After the first, the osmolarity of the blood plasma in puppies rose to 526 m osm/l, 457 m-osm being accounted for by "hyperclectrolytaemia", after the second, decreased to 232 m osm/l (Fig. 1). There

was a water loss of over 20 per cent of body weight in the first case, while in the second an increase in the water content of all organs was observed. Such gross disturbances of homeostasis may partly be due to the fact that although the extracellular body fluids occupy a relatively high percentage

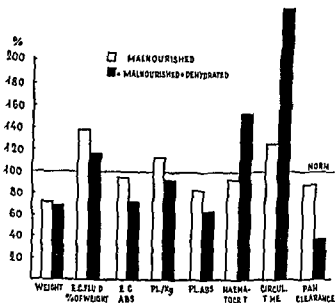


FIG. 2 Extracellular fluids, circulation and PAN clearance in the dehydration of a malnourished infant

Values are represented as percentages of those found in

White column before diarrhoea
 Black column after diarrhoea
 E.C. — extracellular H — plasma

of the body weight, the water reserves in infants are low in relation to the functions they may be called upon to perform.

In order to reconcile this apparent contradiction, it is helpful to consider the relationship of body fluid reserves to circulation and kidney function in malnourished infants. Malnutrition does not affect all systems of the body equally, fat and muscle sustaining greater losses than the extracellular

fluid compartment. Hence the size of the latter appears to increase with the progress of malnutrition (Kerpel Fronius and Kovach, 1948, McCance, 1951, Keys *et al.*, 1950). Haemodynamically, however, it is not the amount relative to body weight but the absolute amount of extracellular fluid which is of importance. Fig 2 illustrates a striking example of a case studied in comparison with well nourished infants of the same length, first in a state of malnutrition and later after dehydration due to diarrhoea had supervened. In the malnourished infant the volume of the extracellular fluid showed a percentage increase before and even after diarrhoea. However, the 'absolute amounts', i.e. the fluid volumes calculated as percentages of those in normally nourished infants of the same length, were decreased. Since the haematocrit readings were high the circulation time prolonged, and the renal clearances low, high water reserves calculated as a percentage of the body weight were clearly insufficient to maintain circulation and kidney function. The absolute volume of the water reserves and not just the amounts proportional to the body weight must be maintained in order to conserve a normal circulation and good renal function.

Let us now consider the normal infant. When compared with the adult, his extracellular water reserves—although high in terms of percentage of body weight—are strikingly low in relation to other physiological needs, namely oxygen consumption, insensible perspiration and cardiac output (Fig 3).

Thus when compared on the basis of body surface, the infant appears to have the same oxygen consumption and cardiac output as the adult, but his systolic output (stroke volume) and plasma volumes are only half those of the adult, in order to achieve the requisite cardiac output with a relatively low plasma volume, the pulse rate is double that of the adult. His inulin and *p* aminohippuric acid (PAH) clearance values are low in comparison with those of the adult and also in relation to his own cardiac output and metabolism. All his fluid compartments are strikingly low in proportion to metabolism, insensible perspiration and cardiac output.

Alternatively, on the basis of *body weight*, the infant's metabolism, dermal loss of water and cardiac output appear to be very high in relation to his total body water and plasma volume, which occupy approximately the same space as in the

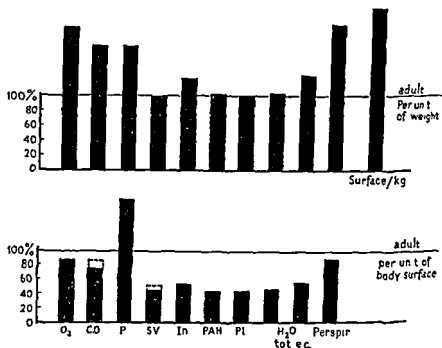


FIG 3 Haemodynamics fluid spaces and renal function of the infant as percentages of values for the adult

— — — — — percent mean values for five infants aged 4 months with body surface as of 0.30 m². The unit of body weight is not shown

CO — cardiac output P — pulse rate, SV — systolic volume, In — inulin Pl — plasma e.c. — extracellular

adult This relationship holds true also for the extracellular fluid volume, although this is higher than in the adult Renal clearances are proportional to fluid volumes and therefore low in relation to circulatory and metabolic rates

Despite the marked differences between adults and infants in some of the physiological constants which have been mentioned these functions are certainly nicely adjusted to each other even in the infant, and his defence mechanisms are fully capable of meeting the normal demands upon them. When put under stress however, the fragility of the whole system which maintains body fluid homeostasis is exposed.

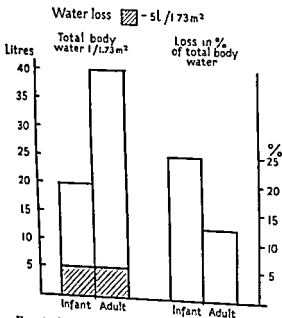


FIG. 4 Significance of "equal" losses when expressed per unit of body surface

Under pathological conditions the consequences of the peculiar interrelationship of these functions are as follows

(a) Water or salt loads calculated according to surface area will in relation to total body water content, be double the values of the adult. The same holds true for loss of water, equal losses per unit of surface area being twice as high in the infant in proportion to the body water (Fig. 4)

Alternatively, on the basis of *body weight*, the infant's metabolism, dermal loss of water and cardiac output appear to be very high in relation to his total body water and plasma volume, which occupy approximately the same space as in the

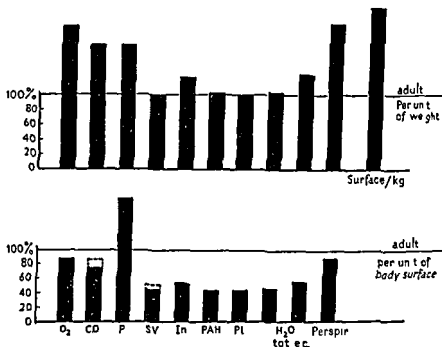


FIG 3 Haemodynamics fluid spaces and renal function of the infant as percentages of values for the adult

— * — of mean values for five infants aged 4 months, with body m². The ly weight, nt, shows percentage

differences between adult and infant

CO — cardiac output P — pulse rate, SV — systolic volume, In — inulin, Pl — plasma, e c — extracellular

adult This relationship holds true also for the extracellular fluid volume, although this is higher than in the adult Renal clearances are proportional to fluid volumes and therefore low in relation to circulatory and metabolic rates

may be threatened either by high urine volumes or, in the case of renal inadequacy, by uraemia

In summary, the mechanisms defending body fluid equilibrium in the infant are more easily broken down owing to the water reserves being low in relation to the high metabolic rate and "strained" circulation. In circumstances of shortage this small water pool is quickly exhausted, and it is also easily flooded by loads which, in terms of body surface, are equal to those for adults. By decreasing the small plasma pool rapidly, water losses lead to slowing down of circulation. Owing to the rapidly decreasing renal clearances, as well as the high metabolic rate producing solutes at great speed, the relatively small water pool cannot then keep up its constancy. Deterioration is accelerated by arrested growth.

In conclusion a particular type of dehydration in which the infant seems to be in a somewhat less difficult position than the adult may be mentioned. In infantile pyloric stenosis, a condition in which starvation and dehydration develop together, a sharp decrease of about 50 per cent in oxygen consumption has been observed by Varga (1957). We have found that this diminution in oxygen requirements protects against stagnating anoxia brought about by the slowing down of circulation due to dehydration (Kerpel *et al.*, 1957). It is probably thus delay in the dehydration process, since the metabolic rate decreases less in the semi starved adult (Keys *et al.*, 1950), the infant may possibly be more resistant to dehydration when he is already suffering from starvation than an adult under similar circumstances.

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 Kerpel-Fur, 1957.

(b) Water deprivation quickly exhausts the water reserves which are low in relation to metabolism and, consequently, to obligatory urine volume and dermal loss of water.

(c) Because of the high cardiac output required for metabolic processes, and the low reserves of water to guarantee its maintenance, circulation is endangered by even smaller water deficits, the more so since water losses occur rapidly. It will be remembered that the small plasma volume of the infant relative to the cardiac output is compensated for by a high pulse rate to ensure adequate circulation.

(d) The vulnerability of the circulation facilitates a rapid decrease in renal clearances, which even in the healthy infant are low in relation to his high metabolic rate. Obviously, the infant's rather poor renal blood flow is adjusted to, and only maintained by a relatively high cardiac output. The renal fraction has been calculated to be 10 per cent of the total output of the heart in infants whereas it is 20 per cent in adults.

As pointed out by McCance and Widdowson (1957) stagnation of growth plays a rôle in the easily disturbed equilibrium. In a growing animal a certain amount of the food goes to the building of its tissues. If growth is arrested, an additional solute load formed by this fraction of the intake presents itself for excretion by the kidneys. This will result either in a higher urine volume, or, if the kidneys are incompetent, in hyponatraemia and azotaemia. McCance and Widdowson (1957) have shown that these effects are striking in fast growing animals and may under certain circumstances be of importance to the human infant. On the basis of some of the data compiled by the American Academy of Pediatrics (1957) an estimate has been made of the effect of arrested growth on solute load and renal water expenditure. Solute load may be expected to rise 18 per cent in the infant who is fed on cow's milk, and 57 per cent in the breastfed child causing a considerable increase in urine volume. When at the same time extrarenal water expenditure is increased by high environmental temperature, or diarrhoeal losses, the water balance

With a very high pulse rate and low cardiac output there must be a high peripheral resistance. This is the case in the newborn. The peripheral resistance is high, and the cardiac output is low.

Young: The great value of this paper is in explaining why the baby is more susceptible to the effects of drugs.

Heller: We are always talking about the large body water content or the high extracellular fluid content.

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DISCUSSION

Dawson Has the subject of size *per se* been considered as opposed to immaturity? The pulse rate of the baby was mentioned as being faster than that of the adult and the reasons for it were based on the immaturity of the organism, whereas one finds that small adult animals have very fast pulse rates. The rabbit pulse, for instance, is well into hundreds and the mouse pulse is even faster.

Young I do not think it has been suggested that the pulse rate is fast because of immaturity. It is high because of the high metabolic rate in relation to the other constants, and in order to keep up the cardiac output.

Adolph The effect of body size on functions such as pulse rate and respiration rate varies considerably in any one species. Among vari-

that none of the body size rules apply uncomplicatedly during illness. There are other factors, and perhaps the factor of metabolic peculiarity is one of them.

McCance Would anyone with paediatric experience like to comment

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Young When this infant became dehydrated he still had a relatively high volume of extracellular fluid as a percentage of body weight, but

THE EFFECT OF HORMONES OF THE PITUITARY AND ADRENAL GLANDS ON THE ELIMINATION OF SODIUM, POTASSIUM AND A WATER LOAD IN INFANT RATS DURING THE WEANING PERIOD

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JARMILA KŘEČKOVÁ and ZDĚNEK VACEK

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Medical Faculty of Charles University Prague*

HOMEOSTATIC mechanisms in infant animals differ from those in adults of the same species. Mechanisms regulating the metabolism of water and electrolytes change immediately after birth, during the period the eyes open, at the time of weaning in connexion with sexual maturation and perhaps also at other stages of postnatal development. In the present paper we should like to draw attention to the time of weaning which seems to us to be one of the important stages in the development of the regulation of water and electrolyte metabolism.

The preweaning period in rats is relatively long. Up to the 14th day of life infant rats cannot survive without the mother rat. They are usually weaned at the end of the third week but according to breeders natural weaning occurs only at the end of the fourth week. This agrees with the development of thermoregulation, for infant rats can survive very low environmental temperatures without the mother only at the end of the fourth week (Čapek *et al.*, 1956).

Up to the 14th or 18th day infant rats live on breast milk only. This is the only source of water and electrolytes, if we disregard the urine of litter mates that is sometimes sucked by the infant animals. From that time onward infant rats in addition to breast milk also actively feed on solid food and

nearer its adult composition in foetal life than the skeletal muscle. I think a great deal of this change is in the skeletal muscle and not in connective tissue.

Fourman · Then is there a difference in the mode of growth of skeletal muscle on the one hand, and liver and heart on the other? Does skeletal

Fourman · If the extracellular fluid is considered as a film over the cells,

test that,

because cell size data based on nucleic acid determinations are available for many different ages in a number of species, and equally, extracellular fluid determinations are available in the same tissues.

ment

Fourman · Dr Shock, is the water content in the muscle larger in old people than in the young ones, since muscles do atrophy in old age? We have had that answered indirectly in Dr Olesen's paper, but are there any direct analyses?

Shock · I cannot answer for the human, but we have some data on the electrolyte and water composition of rat muscle tissue. We found that

decreased. The potassium, phosphorus, and nitrogen contents all went down, but the chloride and sodium contents went up. The ratio of potassium to nitrogen and of phosphorus to nitrogen remained constant. Our interpretation of this was in the light of our beliefs about the reduction in active protoplasm in old age. It is as if a certain mass of protoplasm had disappeared and been replaced by extracellular compounds with the appropriate amount of sodium and chloride to make up the total water composition.

Fourman · As I said, it is not a replacement, but—to borrow Dr. Davson's expression—a geometrical necessity to keep a film of water around the cells.

Kennedy · But you would need to know whether the atrophy was due

of the kidneys to eliminate an administered water load changes and its ability to concentrate increases. According to Falk (1955), however, infant rats older than three days already react to vasopressin by cessation of diuresis and an increased excretion of chloride. As both authors use different methods it seemed useful to study this problem first, using several methods, and also to study the effect of vasopressin on the elimination of sodium and potassium. Opinions on the natriuretic effect of vasopressin also differ and we believe that this is due to different methodological approaches. Schaumann (1949) and Heller and Stephenson (1950) observed that vasopressin decreases the excretion of sodium in adult rats, while Sawyer (1952) observed an increased elimination of this electrolyte. The former authors administered the hormone at the same time as the water load. Sawyer first slightly prehydrated his animals and then gave them the hormone and the water load. According to Heller (1952) the ability of the rat kidney to eliminate a water load changes at the time of weaning. We therefore always used rats with a water load.

Infant rats were weaned on the 15th-16th day after birth and the whole litter left in one cage. They received a standard synthetic diet without sodium chloride. They were allowed to choose between water and a 3 per cent sodium chloride solution. As we expected changes in the mechanisms studied to occur at the end of the fourth week, infant animals aged 23 and 33 days were used. Loads of warm distilled water were administered via a stomach tube in amounts of 4-5 ml/100 g body weight. Subcutaneously the animals received saline (0.5 ml/100 g body weight) in which the substances studied were dissolved. The elimination of a water load was studied for three hours after its administration or, in the case of vasopressin, for three hours from the first micturition. Urine was collected at hourly intervals. The amount of urine, together with the concentration of sodium and potassium, was determined by use of a flame photometer.

Adult rats rapidly excrete urine with a low content of

drink water. Gradually the mechanisms for compensation of thirst and hunger separate. At the end of the fourth week infant animals cease to feed on breast milk and take in food that is normal for adult animals.

We studied the active intake of water, electrolyte solutions and milk in infant rats using the method of free choice as known especially from the work of Richter (1936), Young (1949), and Young and Chaplin (1949). We observed that in infant rats weaned at the beginning of the third week of postnatal life there is a significant change in the regulation of water, electrolyte and milk intake at the end of the fourth week. The regulation of sodium intake in relation to water intake, especially, changes. According to Richter (1936) appetite for individual components of the diet is an important homeostatic mechanism and is determined by the needs of the organism.

In order to be able to offer a physiological explanation for changes in the regulation of sodium intake it is necessary to throw light on the relation between mechanisms of self selection and other components of water and electrolyte metabolism that can be studied better and more objectively.

The adrenals and the posterior lobe of the pituitary are of special significance for the regulation of water and electrolyte metabolism. For this reason we have studied the effects of hormones from these two glands. Up to the present nothing is known of a change in function of the adrenals or in the effect of their hormones at the end of the fourth week of life in the rat. Indirectly one might expect such a change from the fact that the regulation of sodium intake depends on the function of the adrenals (Richter, 1936). There is also no difference in the size of the glands in males or in females during the fourth week.

More is known about changes in the rôle played by the posterior lobe of the pituitary during this period. Heller (1952) showed that up to the end of the fourth week of life the rat kidney does not react to vasopressin during a water load in the same way as that of the adult. In addition the ability

Older animals, however, excrete nearly half the water administered and thus excrete body water via the kidneys. Differences in sodium excretion are also apparent. Thirty-three day-old animals excrete three times as much body sodium as younger rats. The difference between both age groups studied disappears completely, or becomes much smaller, if 2.5 ml water/100 g body weight is put into their stomachs two and a half hours before the actual water load. In that case more urine is excreted by the younger animals and losses are reduced in the older age group. Sodium losses are also decreased in the older age group to the same level as in 23 day-old animals. No significant changes in potassium excretion were observed.

Differences between the two age groups are thus not constant. For this reason we assume that the difference is not due only to changes in renal function but that regulatory mechanisms are involved.

On the day of the water load, the water load was studied according to the method of Falk (1955). In addition the effect on total water loss three hours after the first micturition was studied. This procedure was similar to that of Heller (1952) who determined total renal excretion of a water load 145 minutes after administration of the hormone and the water load.

After 10 or 25 m u vasopressin/100 g body weight, no significant differences between the two age groups could be observed during water diuresis. This is in agreement with Falk (1955). Yet 23-day-old animals react differently to vasopressin than 33-day-old rats. This difference can be seen in Table I. After a single water load vasopressin (the table shows the results with 25 m u /100 g body weight) increases renal water losses in the younger animals, while in the older group total renal water losses are reduced. The sodium loss in older animals treated with vasopressin becomes greater after prehydration only. In younger animals the elimination of potassium is significantly greater than in the

sodium and potassium after administration of a water load
Males excrete a water load less well than females

In our experiments the excretion of a water load was the same in infant rats as in the experiments of Heller (1952)

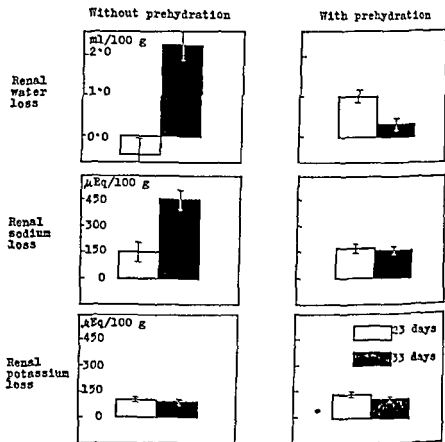


Fig. 1. The renal loss of water, sodium and potassium in infant rats after administration of a water load.

There are no sex differences. There are, however, considerable differences between infant animals aged 23 and 83 days. These can be seen in Fig. 1. Twenty-three day old animals do not eliminate the total water load within three hours

Older animals however, excrete nearly half the water administered and thus excrete body water via the kidneys. Differences in sodium excretion are also apparent. Thirty three day old animals excrete three times as much body sodium as younger rats. The difference between both age groups studied disappears completely, or becomes much smaller, if 2.5 ml water/100 g body weight is put into their stomachs two and a half hours before the actual water load. In that case more urine is excreted by the younger animals and losses are reduced in the older age group. Sodium losses are also decreased in the older age group to the same level as in 23-day-old animals. No significant changes in potassium excretion were observed.

Differences between the two age groups are thus not constant. For this reason we assume that the difference is not due only to changes in renal function but that regulatory mechanisms are also concerned.

The effect of vasopressin was studied in animals receiving one water load and in prehydrated rats. The elimination of the water load was studied according to the method of Falk (1955). In addition the effect on total water loss three hours after the first micturition was studied. This procedure was similar to that of Heller (1952) who determined total renal excretion of a water load 145 minutes after administration of the hormone and the water load.

After 10 or 25 m u vasopressin/100 g body weight, no significant differences between the two age groups could be observed during water diuresis. This is in agreement with Falk (1955). Yet 23-day-old animals react differently to vasopressin than 33 day old rats. This difference can be seen in Table I. After a single water load vasopressin (the table shows the results with 25 m u/100 g body weight) increases renal water losses in the younger animals, while in the older group total renal water losses are reduced. The sodium loss in older animals treated with vasopressin becomes greater after prehydration only. In younger animals the elimination of potassium is significantly greater than in the

Table I

THE EFFECT OF VASOPRESSIN ON SODIUM AND POTASSIUM EXCRETION AND WATER LOSS AFTER WATER LOAD IN PREHYDRATED AND UNPREHYDRATED RATS OF DIFFERENT AGES

| | Age of animals in days | Sodium excretion | | Potassium excretion | | Renal water loss | |
|---|------------------------|------------------|------------------------------------|---------------------|------------------------------------|------------------|---------------------------|
| | | No of animals | μ equiv / 100 g body wt / 3 hr | No of animals | μ equiv / 100 g body wt / 3 hr | No of animals | ml / 100 g body wt / 3 hr |
| Water load 4.5 ml / 100 g body wt H_2O via stomach tube + 0.5 ml / 100 g body wt saline s.c. without prehydration | 23 | 7 | 147 \pm 50.4 | 8 | 90 \pm 0.7 | 8 | -0.5 \pm 0.4 |
| | 33 | 8 | 450 \pm 45.5 | 7 | 85 \pm 13.7 | 8 | 2.3 \pm 0.38 |
| Water load 4.5 ml / 100 g body wt H_2O via stomach tube + 2.5 m.u. / 100 g body wt vasopressin in 0.5 ml / 100 g body wt saline s.c. without prehydration | 23 | 7 | 187 \pm 28.3 | 5 | 123 \pm 62.5 | 7 | 0.0 \pm 0.36 |
| | 33 | 8 | 350 \pm 36.0 | 7 | 113 \pm 18.1 | 7 | 1.4 \pm 0.18 |
| Water load 1.5 ml / 100 g body wt H_2O via stomach tube + 0.5 ml / 100 g body wt saline s.c. with prehydration | 23 | 15 | 168 \pm 24.3 | 16 | 135 \pm 13.0 | 15 | 1.0 \pm 0.24 |
| | 33 | 14 | 154 \pm 21.3 | 14 | 109 \pm 11.4 | 16 | 0.3 \pm 0.215 |
| Water load 4.5 ml / 100 g body wt H_2O via stomach tube + 2.5 m.u. / 100 g body wt vasopressin in 0.5 ml / 100 g body wt saline s.c. with prehydration | 23 | 16 | 245 \pm 36.2 | 16 | 173 \pm 10.3 | 16 | 1.4 \pm 0.32 |
| | 33 | 13 | 255 \pm 29.0 | 13 | 123 \pm 13.0 | 16 | -0.1 \pm 0.41 |

33 day old rats Thus vasopressin has a different effect in 23 day old than in 33 day old animals Evidently there is a

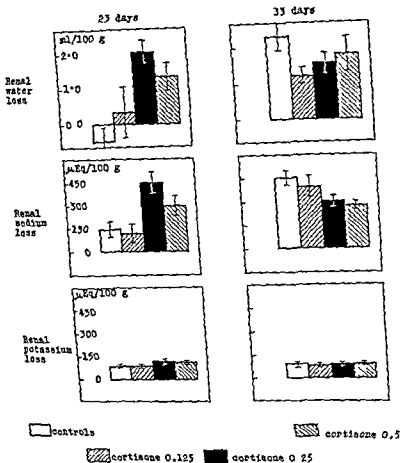


Fig 2 The effect of cortisone administered for six days in different doses on renal loss of water sodium and potassium during the first three hours after administration of a water load (4.5 ml/100 g body wt) to young rats aged 23 and 33 days

change in the reactivity of the kidneys to this hormone at that period This might be due to functional differences in

kidney parenchyma or to the fact that from the end of the fourth week a regulatory factor is present which can be influenced by loading the organism with water. It therefore seemed all the more interesting to us to find out whether the function of the adrenals changes at the time of weaning.

After adrenalectomy the ability to eliminate a water load is strongly reduced in infant rats. It is difficult therefore to use this method for solving the problem. A less direct way was chosen — a study of the effect of substances that act in a similar way to the main corticoids. Cortisone or cortexone was administered for six days in various doses to 18–23 and 28–33 day old animals. Then a water load was given. It appeared that the effect of these substances also depends on the age of the rats.

The effect of cortisone is shown in Fig. 2. The elimination of a water load, sodium and potassium was determined in rats that received 0.125, 0.25 or 0.5 mg cortisone/100 g body weight. The hormone has opposite effects in the younger and in the older age groups. In 23 day old animals it increases the excretion of water (as it does in the 3 day old rats of Falk, 1955) and sodium, while in the 33 day old rats it decreases both. After a dose of 0.25 mg/100 g body weight, renal water and sodium losses in the younger animals reach the level of the older control animals. It is evident that the effect of cortisone compensates for the deficiency of aldosterone in younger animals but present in the older rats. This, however, is not borne out by the way in which a water load is eliminated by the younger rats after cortisone. Fig. 3 shows changes in the concentration of sodium in the urine during the course of water diuresis in normal animals and after cortisone (0.25 mg/100 g). In the control 33 day old animals the concentration rises as the intensity of water diuresis falls. In the younger group there is no such relationship and the concentration is not lowest during the highest diuresis. If cortisone were only a substituting substance the course of the curves of sodium concentration ought to be the same in 23 day old rats receiving cortisone.

and 83-day old controls. As this is not the case and as in the younger animals increased natriuresis is mainly due to increased concentration at the time of maximum water

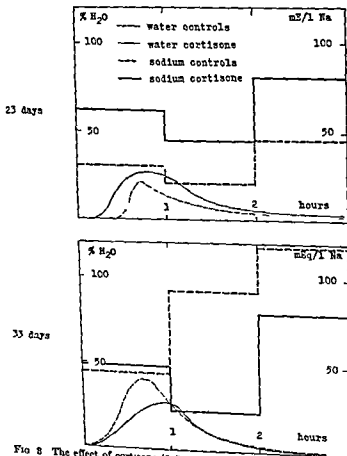


FIG. 8 The effect of cortisol (0.25 mg/100 g body wt./day) on the course of the excretion of a water load and the concentration of sodium in the excreted urine in infant rats aged 23 and 33 days

diuresis, relations are evidently more complex. This is also borne out by the fact that the effect of cortisol in the younger group is variably dependent on the dose used.

This is even more evident in the case of cortexone. This was administered by the same route as the former substance

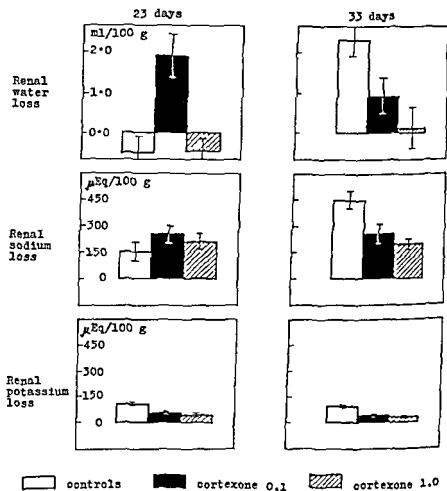


Fig. 4. The effect of different doses of cortexone on renal water, sodium and potassium loss.

but in doses of 0.1 and 1 mg./100 g. body weight. Results are shown in Fig. 4. Lower doses of cortexone had an effect similar to cortisone, quantitatively different in younger and

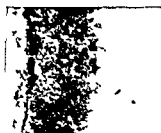
23 days

33 days

Controls



Cortisone



ACTH

Cortisone
+ ACTH

FIG. 5 The effect of cortisone (0.2 mg/100 g body wt/day) and ACTH (0.2 iu/animal day) administered for six days on the size of the adrenal cortex in young rats aged 23 and 33 days. Stained with Sudan Black.

older animals. In younger animals it increased renal losses, which thus nearly reached the levels of the older controls. In 33 day old animals water losses decreased after cortexone. The higher dose, however, had no effect on renal losses of water in 23 day old animals, whereas in 33 day old rats it further decreased renal losses. These doses, however, are probably toxic. Sodium losses were never significantly altered by either dose of cortexone in the younger group. In 33 day old animals they changed in direct proportion to the dose used. In both age groups cortexone decreases renal potassium losses significantly.

Thus corticoids have a different effect on the elimination of water and electrolytes after a water load in infant rats that have not yet reached the age at which they are normally weaned, than they have in older animals. The opposite effects in 23 day old animals, depending on the dose used, indicate that these hormones cause changes that mutually interfere with each other.

We attempted to determine whether in addition to the pharmacodynamic effect of these hormones there is also an effect on the regulation of adrenal activity.

The weight of the adrenals of animals receiving cortisone or cortexone, as indicated above, dropped to about the same extent in both 23 and 33 day old animals. Simultaneous administration of ACTH in amounts usually sufficient to maintain adrenal weights of hypophysectomized animals (0.2 i.u. per animal) prevents adrenal atrophy in both groups. This reaction is less obvious on histological studies. Fig. 5 shows microphotographs of the adrenal cortices of 23 and 33 day old -

1. *ACTH Preparations*
were stained with Sudan Black so that both the width of the cortex and the sudanophil layers can be seen. After ACTH there are no obvious changes in the width of the cortex and the sudanophil layer. After cortisone and cortisone plus ACTH differences are evident. This is even more apparent.

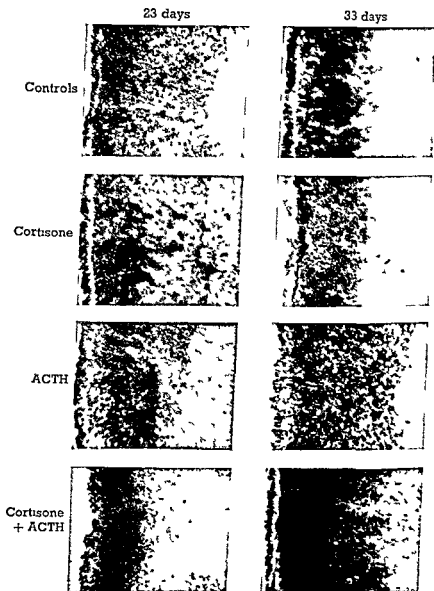


FIG. 5 The effect of cortisone (0.25 mg/100 g body wt/day) and ACTH (0.2 iu/animal/day) administered for six days on the size of the adrenal cortex in young rats aged 23 and 33 days. Stained with Sudan Black.

of the sudanophil layer increases in both age groups but in the younger group the size of the whole cortex is smaller. It is difficult to interpret these changes. It is certain, however, that according to morphological criteria the adrenals of the 23-day old animal react differently from those of the animal aged 33 days. This would indicate that changes in the reactivity of infant rats to a water load at the end of the natural period of weaning and to corticoids are also conditioned by a different reactivity of the adrenals and the adrenopituitary system.

This hypothesis is further supported by results from experiments in which the effect of ACTH and a combination of ACTH and cortisone (0.25 mg/100 g) was studied on the elimination of water, sodium and potassium after a water load. Results are shown in Fig. 7. As has already been shown, cortisone prevents retention of a water load in 23 day old animals and considerably increases renal water losses. ACTH is without effect. After simultaneous administration of ACTH and cortisone, water losses decrease in comparison to losses after cortisone only. In 33 day old rats results are less evident because of the large scatter. ACTH itself causes an increase in sodium excretion in 23 day old animals but in combination with cortisone it is without effect on sodium elimination and thus removes the latter's natriuretic effect. This effect is probably due to the lower renal water losses. In 33 day old animals ACTH decreases sodium losses just as do cortisone and cortisone combined with ACTH. The same holds good for ACTH when combined with cortexone. ACTH prevents atrophy of the adrenals after cortisone in infant rats aged 23 days and also prevents the effect of cortisone on sodium and water elimination. This is not the case in older animals. This is in agreement with the histological picture and with the differences between 23 and 33 day old animals.

We have thus been able to show that there is a time correlation between changes in homeostatic mechanisms regulating the intake of water and electrolytes appearing in infant rats at the time of natural weaning, and adrenal

in Fig 6, which shows the results of micrometric measurements of the width of the cortex and the sudanophil layer as obtained from serial sections of the adrenals. Four adrenals from each group were measured. One hundred sections from each gland were used and measurements were taken from

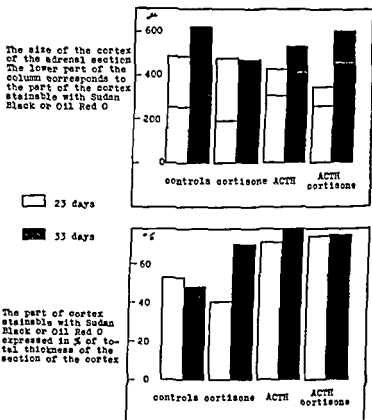


Fig 6 See Fig 5

several sites of those sections. Differences are largest after cortisone. In 23 day old animals the sudanophil layer decreases in size while the total width of the cortex remains unchanged. In 33 day old animals the width of the cortex decreases and thus the relative width of the sudanophil layer is increased. After ACTH and cortisone the proportion

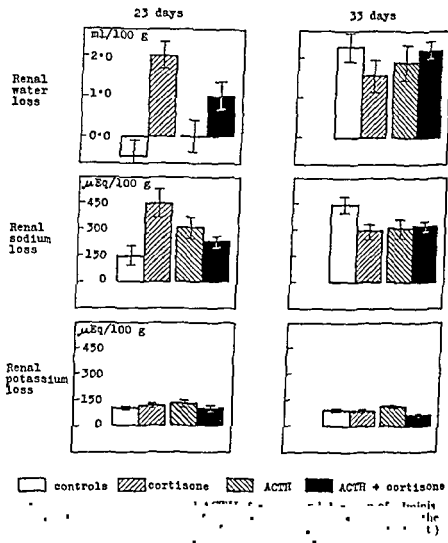
This is probably conditioned by the presence of a regulating mechanism which after previous loading with water increases the reabsorption of sodium. At the end of the preweaning period there is a considerable change in the effect of cortisone and cortexone on elimination of water and sodium after a water load. Even 33 day old animals, however, do not react quantitatively in the same way as adult animals. Thus is evidently due to the fact that only after the 33rd day does the male adrenal begin to differ from that of the female. It may be assumed from the results presented here that the reactivity of the adrenals changes at the time of weaning. That change can be in relation to the change in homeostatic mechanisms regulating the intake of water and sodium which occurs at the time of weaning.

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[Discussion of this paper was postponed until after the paper by Dr Desaulles—Eds.]

pituitary mechanisms regulating the metabolism of water and electrolytes At the end of the fourth week of life the effect



of vasopressin on elimination of a water load changes. This is in agreement with Heller (1952). In addition, at this time vasopressin begins to have an effect on sodium elimination

own adrenals, as well as to avoid strain bound differences in sensitivity

To test the action of steroids on urinary and electrolyte excretion, we have used the method described in detail by Desaulles and Meier (1956), the only difference being that, instead of collecting urine from the catheter - at 1 - 6

first to the third hour, from the second to the fourth hour, and from the seventh to the ninth hour following treatment, thus procedure enabling us to follow closely the excretion of urine and of electrolytes Both male and female animals were used, the age groups being

- (a) animals about five weeks old and about 50 g in weight,
- (b) animals about 15 weeks old and about 150-180 g in weight,
- (c) animals about one year old and exceeding 300 g. in weight

All animals used in these experiments were kept isolated in metal cages

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beginning of the experiment

The steroids chosen, aldosterone and cortisol, are known to be secreted by the rat adrenals (Bush, 1953, Singer, 1957) Cortisol was used as free alcohol, aldosterone was used as DL aldosterone acetate, the activity of which is just one half of D aldosterone (Schmidlin *et al*, 1955, 1957) All substances were dissolved in sesame oil and injected intramuscularly

The doses used in these experiments were chosen from previous experiments (Desaulles and Meier, 1954, Desaulles, 1958) and lay within a dose range corresponding to sub maximal effects For aldosterone acetate 0.01 mg/kg was given, and for cortisol 5 mg/kg

As the excretion of urine and urinary electrolytes differs

DIFFERENCES IN THE PATTERN OF ELECTROLYTE AND WATER EXCRETION IN YOUNG AND OLD RATS OF BOTH SEXES IN RESPONSE TO ADRENAL STEROIDS

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It is a known fact that, with advancing age, the cell mass and, correspondingly, the cell water content of the animal decrease. This, together with a constant or increasing extracellular water content, appears to be one of the true signs of ageing (McCance and Widdowson, 1951, Olbrich and Woodford-Williams, 1956).

Although the adrenals, and more especially the adrenal steroids, play an important part in the maintenance of the water and electrolyte balance, only comparatively little is known about the influence of age on the activity of the adrenals or on the sensitivity of the organism to adrenal steroids in animals. We were therefore prompted to study in rats of different ages the pattern of urine and urinary electrolyte excretion after treatment with two genuine adrenal steroids, aldosterone and cortisol, following a load of physiological saline solution amounting to 20 ml per kg.

In view of the very complex interrelationship existing between pituitary, gonads, and adrenals during the development of the animal from birth to maturity and old age, we have also studied rats of both sexes. These animals were chosen in three different groups, ranging in age from (a) five weeks to (b) fifteen weeks to (c) one year and more.

Methods

All experiments were performed on adrenalectomized rats of the same breed, in order to avoid interference between the steroids injected and the steroid output of the animal's

Aldosterone prevents sodium excretion in a very marked manner in about the same intensity and for about the same duration (five to seven hours) in all age groups (Fig 2)

The only difference to be noted is that in old animals the onset of the sodium retaining effect of the steroid is retarded,

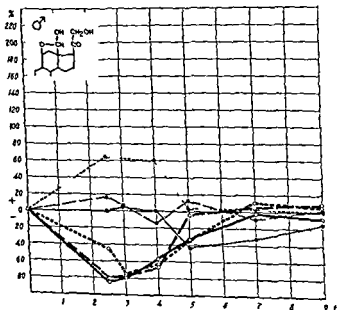


Fig 2 Urinary sodium and potassium excretion of adrenal e tomized male rats of different age groups treated with aldosterone (0.010 mg/kg)

Thick line sodium excretion
Thin line potassium excretion.
Other figures as for Fig 1

the maximal effect falling in the collecting period of the third hour instead of in the preceding period

The effects of aldosterone on potassium excretion depend upon the age groups in question

In young animals aldosterone does not affect potassium excretion until the fourth collecting hour. From the fifth

in amount in animals of differing age and weight, the results are expressed as percentages of the values of control animals for urinary excretion in ml, and for sodium and potassium excretion in m mole. The differences between the sodium/potassium ratios of treated and control animals are, on the other hand, expressed in absolute values.

Results

Effect of aldosterone

In the *male rat*, aldosterone produces a marked inhibition of urinary output that is most pronounced in young animals

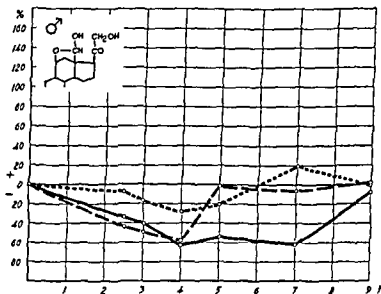


FIG 1 Urinary excretion of adrenalectomized male rats of different age groups treated with aldosterone (0.010 mg/kg)

Abscissa: Duration of experiment (hours) collecting period 2 hours

Ordinate: Urinary excretion as a percentage of the values of control animals

Continuous line: 5 week-old rats

Interrupted line: 15 week old rats

Dotted line: one year and more old rats

and tends to diminish—at first in duration and then in intensity—with increasing age (Fig 1)

Aldosterone prevents sodium excretion in a very marked manner in about the same intensity and for about the same duration (five to seven hours) in all age groups (Fig. 2).

The only difference to be noted is that in old animals the onset of the sodium retaining effect of the steroid is retarded,

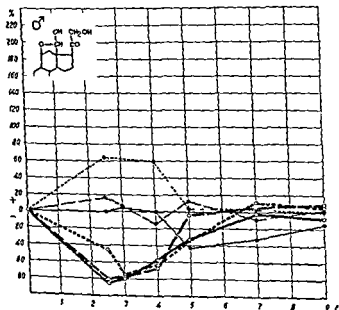


FIG. 2 Urinary sodium and potassium excretion of adrenal ectomized male rats of different age groups treated with aldosterone (0.010 mg/kg)

Thick line . sodium excretion
Thin line . potassium excretion
Other figures as for Fig. 1

the maximal effect falling in the collecting period of the third hour, instead of in the preceding period

The effects of aldosterone on potassium excretion depend upon the age groups in question.

In young animals, aldosterone does not affect potassium excretion until the fourth collecting hour. From the fifth

hour onward it induces a clear cut reduction in potassium excretion, which reverts to normal in the ninth hour. On animals of the adult group aldosterone has practically no effect at all. In old rats, however, aldosterone markedly enhances potassium excretion.

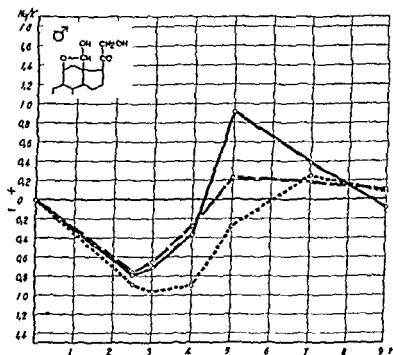


FIG. 3. Urinary sodium/potassium ratio of adrenalectomized male rats of different age groups treated with aldosterone. Ordinate: Difference between sodium/potassium ratio of experimental animals and controls. Other figures as for Fig. 1.

If we consider the sodium/potassium ratio, we observe that aldosterone reduces it markedly during the first hours of the experiment in all groups (Fig. 3), its maximum occurring in the first collecting period for young and adult groups, and showing a certain delay (three hours) and greater intensity (-0.95 against -0.75 to -0.80) in the old age group. From the fourth hour onward there is an increase in the ratio for

young animals (due to potassium retention), whereas adult and old animals return to a range within control values, the adult group reacting more readily than the old animals

In the *female rat*, aldosterone also reduces the urinary output, but to a somewhat smaller extent than in males (-40 per cent on the average, against about -60 per cent in males) (Fig 4) As in males, young animals tend to respond more



FIG 4 Urinary excretion of adrenalectomized female rats of different age groups treated with aldosterone (0.010 mg/kg)

Figures as for Fig 1

markedly although there is a certain delay in the onset of the effect. In contrast to males, with increasing age a short period of urinary retention is followed by a strong diuretic response.

On sodium excretion aldosterone exerts a very pronounced inhibiting effect of about the same relative intensity as in males in all age groups (Fig 5). In contrast to that in males, this effect is followed by a period of sodium excretion, most marked in old animals ($+80$ per cent), the values returning towards the norm in the ninth hour.

On potassium excretion the enhancing effects of aldosterone are more marked and begin at an earlier age than in males, old animals showing the most pronounced effect

On the sodium/potassium ratio the effects are much more marked than in the case of males (Fig 6) Young animals respond with a reduction that is marked (-0.90), but of slow

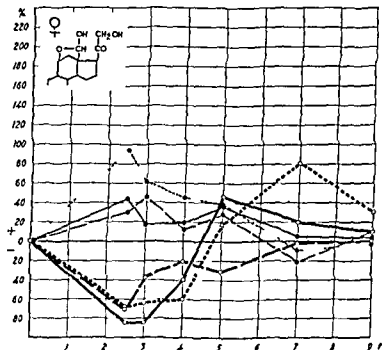


FIG 5 Urinary sodium and potassium excretion of a fenalectomized female rats of different age groups treated with aldosterone
Figures as for Fig 2

onset (maximum in the fifth hour) the values returning to within control limits at the end of the experiment

In adult and old females the reduction in the sodium/potassium ratio is more intense (-1.29 and -1.10 respectively) and rapid in onset (maximum in the first collecting period) This effect lasts longest in old animals

The rapid lowering of the sodium/potassium ratio is

followed, in contrast to the situation for male animals, by a very pronounced and rapid rise (more in adult than in old animals) to high positive values (+0.95 and +1.28, respectively), this effect tending to return within control values in the ninth hour

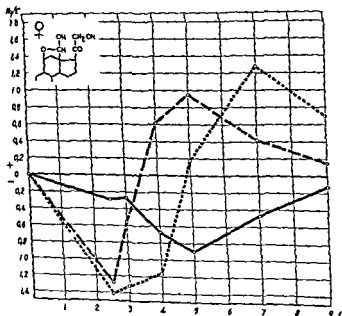


Fig. 6

Effect of cortisol

On sodium, cortisol exerts initially a slight retaining effect that has already been reported (Dorfman, 1949, Johnson, 1950). This effect is well developed, and ageing does not seem to modify it markedly (Fig. 7).

On sodium, cortisol exerts initially a slight retaining effect that has already been reported (Dorfman, 1949, Johnson, 1950).

1954, Desaulles, 1958) and which is followed by enhanced sodium excretion (Fig 8) In males these effects tend to disappear with advancing age

On potassium, one observes the characteristic excretory response whose intensity is particularly high in young animals, its onset being somewhat more rapid in adult and old animals

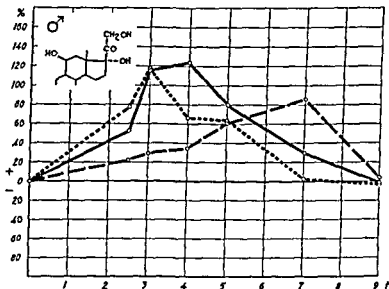


FIG 7 Urinary excretion of adrenalecctomized male rats of different age groups treated with cortisol (5 mg/kg)

Abscissa Duration of experiment (hours) collecting period 2 hours

Ordinate Urinary excretion as a percentage of the values of control animals

Continuous line 5 week old rats

Interrupted line 15 week old rats

Dotted line one year and more old rats

The effect of cortisol on the sodium/potassium ratio is first to lower it moderately in males, and to raise it afterwards to high positive values (Fig 9) This effect, most marked in young animals, declines with increasing age

In female rats, cortisol has a stronger enhancing effect on urinary output than in males (Fig 10) With age, this effect increases and a certain latency of onset seems apparent.

On sodium, cortisol has similar retaining effects in females as in males and these disappear in old animals (Fig 11)

As regards the enhanced sodium excretion which appears later, females react differently from males. Instead of dis

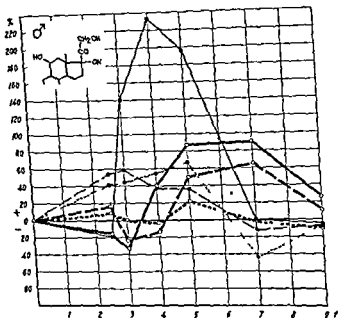


Fig 8 Urinary sodium and potassium excretion of adrenalectomized male rats of different age groups treated with cortisol (> 1 mg/kg)

Thick line sodium excretion

Thin line potassium excretion

Other figures as for Fig 1

appearing with increasing age, the response remains high and its onset is more rapid in ageing females, although in this experiment animals of the adult group do not respond clearly

The effect of cortisol on potassium excretion in females is similar to that observed in males, i.e. it is enhanced, the effects tending to decrease in intensity with age

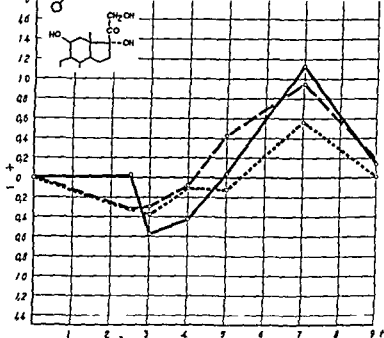


FIG 9 Urinary sodium/potassium ratio of adrenalectomized male rats of different age groups treated with cortisol (5 mg/kg)

Ordinate Difference between sodium/potassium ratio of experimental animals and controls

Other figures as for Fig 1

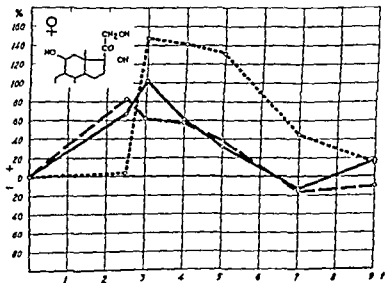


FIG 10 Urinary excretion of adrenalectomized female rats of different age groups treated with cortisol (5 mg/kg)

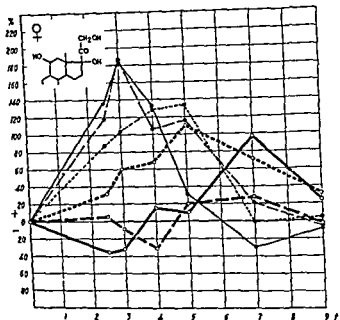
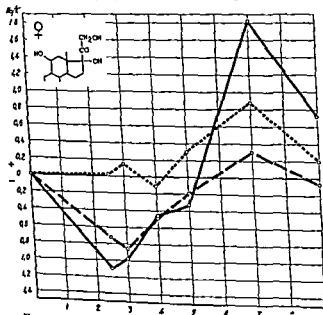


FIG 11 Urinary sodium and potassium excretion of adrenalectomized female rats of different age groups treated with cortisol (5 mg/kg) Figures as for Fig 2



On the sodium/potassium ratio, the effects are comparable to those obtained in males but are of greater intensity (more than twice the values observed in males) and of more rapid onset, and also tend to diminish rapidly with increasing age (Fig 12)

Discussion

From the experimental results presented, it follows that age modifies the sensitivity of adrenalectomized rats to the influence of the adrenal steroids investigated. These modifications are qualitative as well as quantitative, the sex of the animals also playing an important rôle.

Whereas in male rats increasing age tends to reduce to control values the inhibiting effects of aldosterone on urinary output, it tends in females to induce a marked secondary diuretic response. The primary retention of sodium produced by aldosterone is of about the same order of magnitude in all animals, whether male or female, but ageing greatly increases the concomitant loss of potassium, this effect being particularly clear in male and female rats of the old age group.

In contrast, cortisol has an enhancing effect on diuresis which, especially in females, tends to increase with advancing age, whereas in males it is more intense from the onset and remains of about the same order. The effects of cortisol on sodium excretion are profoundly different with advancing age in rats of different sexes. In males these effects tend to disappear completely. In females, on the other hand, they appear earlier and remain of the same order of magnitude.

After cortisol treatment we can observe comparable differences in potassium excretion. Whereas young males respond with an intense potassium excretion which drops rapidly as the animals grow older, these changes are only moderate in females, potassium excretion remaining high until old age and its onset merely retarded.

These age and sex bound differences become particularly clear if we study the variations in the sodium/potassium ratio. The sensitivity of the animals to the effects of aldosterone

increases with advancing age, females showing much greater differences than males. By way of contrast, sensitivity of the animals to cortisol diminishes with advancing age, females showing here too a greater sensitivity than males.

The similarity of the curves of the sodium/potassium ratio for aldosterone and cortisol is also striking and leads us to the problem of (a) the primary and (b) the secondary effects of these substances, and furthermore to the problem of the classification of adrenal steroids on the basis of what has been considered their most important physiological effects.

From previous experiments with aldosterone one is inclined to consider as primary effects both sodium retention as a consequence of increased tubular resorption of sodium ion, and potassium excretion as a consequence of the exchange between sodium ions in the tubule cells (Cole, 1957, Stanbury, Gowenlock and Mahler, 1958). Sodium retention remains of about the same order of intensity and duration from youth to old age in both males and females. It is concomitant potassium excretion that rises strikingly with advancing age both in males and females.

On the other hand, the diuresis induced by aldosterone, which is most apparent in old female animals in the later phases of the experiment, is most probably of secondary origin, its causes lying in the effect of aldosterone on the sensitivity of adrenalectomized animals to endogenous anti-diuretic hormone (Gaunt, Lloyd and Chart, 1956).

As for cortisol, its essential effect seems to be in the very marked potassium excretion which is regarded as running in parallel with its catabolic effects.

Its effect on potassium excretion tends to diminish with advancing age, male animals being here more susceptible than females. Conversely, the diuretic and sodium excretion

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... hormone, these properties tend to disappear with increasing age in males but not in females. Aldosterone and cortisol tend to induce a greater diuretic

response and concomitantly higher sodium excretion with advancing age, especially in females

This, together with the similarity of the changes in the sodium/potassium ratio induced by aldosterone and cortisol during these experiments, even if the factors of ageing and sex act differently on them, underlines certain similarities of effect in a number of known adrenal steroids which have already been stressed (Meier and Desaulles, 1956, Gaunt and Chart, 1958). Relative dosage, time, age, experimental conditions and different stages of homeostasis are among the factors modifying these similar patterns of effect. The relation of homeostasis to the development of the animal organism is too complex to permit of any definite statement. We have simply tried to show that the properties of certain hormones may be profoundly affected by such factors as sex difference and increasing age, and that these differences may act in the same or in quite different ways and thus contribute towards a better understanding of pathophysiological changes due to age.

Summary

It has been shown that in rats of differing age and sex the sensitivity to the influence of aldosterone and cortisol on urinary electrolyte excretion varies greatly.

Whereas age tends to increase sensitivity of the animals to the effects of aldosterone, their sensitivity to cortisol by way of contrast tends to diminish.

On the other hand, female animals show a greater responsiveness to these changes than male animals.

These results are discussed.

Acknowledgement

I should like to express my thanks to Mr H D Phillips (M A Cantab) for his kind assistance in the preparation of the English text of this paper.

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DISCUSSION

Adolph Dr Křeček how do you account for what I take to be an absence of water in the weaned rat?

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Křeček Yes it was because the pattern of the adre-

response and concomitantly higher sodium excretion with advancing age, especially in females

Thus, together with the similarity of the changes in the sodium/potassium ratio induced by aldosterone and cortisol during these experiments, even if the factors of ageing and sex act differently on them, underlines certain similarities of effect in a number of known adrenal steroids which have already been stressed (Meier and Desaulles, 1956, Gaunt and Chart, 1958). Relative dosage, time, age, experimental conditions and different stages of homeostasis are among the factors modifying these similar patterns of effect. The relation of homeostasis to the development of the animal organism is too complex to permit of any definite statement. We have simply tried to show that the properties of certain hormones may be profoundly affected by such factors as sex difference and increasing age, and that these differences may act in the same or in quite different ways and thus contribute towards a better understanding of pathophysiological changes due to age.

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Heller That is almost exactly what we found; our age groups were 20-22 and 29-31 days after birth.

Borst Has Dr. Heller

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Desaulles Ours were done very early in the morning.

Adolph Did you run controls without the hormones?

Desaulles Every group was run with controls.

Borst Light is not important. In blind people the diurnal rhythm remains normal if they are in light during the night and in the dark during the day.

Desaulles We cannot cope with every activity, but we did think that light might be one of the problems.

Fourman Dr. Desaulles, you drew an analogy between the effects of aldosterone and of cortisol on the excretion of sodium and potassium. If one considers the excretion ratio of these two ions in the urine, the effects do appear to be analogous. I read that in the literature that

the effect of cortisol on potassium was across the tissues.

If cortisol on potassium was across the tissues

long as they equate these end effects. The results will not be very reliable if you assay a cellular effect.

Fourman The early rise in potassium excretion with cortisol is probably a cellular effect. The results will not be very reliable if you assay a

hormone by a change in Na/K ratios in the urine, when the change is produced by two different mechanisms.

Desnuelles: I just wanted to show in this experiment that ages bring changes, and sex too.

Na/K ratios.

Milne: I am confused by your statement, Dr Fourman. You make

changes are much less impressive, but there still remains a great difference between the two sexes. I want to stress here a point that is always a little puzzling to me: if you spay a female you produce a marked adrenal enlargement, but if you castrate a male the

find that in young animals there is very little difference in water diuresis as compared to that in animals 33 days old. Between adult animals and 33 day-old ones there is no difference, but between 23 and 33 days there are variable, but statistically significant differences in the excretion of the water load.

Heller That is almost exactly what we found, our age groups were 20-22 and 29-31 days after birth.

Borst Has diurnal rhythm been taken into account by Dr. Desaulles and Dr. Křeček? Big differences can arise if the controls and experiments are not done at the same time each day.

Křeček Our experiments and controls were always done at the same time in the morning. They were done in summer and in winter, with the same results.

Desaulles Ours were done very early in the morning.

Adolph Did you run controls without the hormones?

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interested in the effect of aldosterone on the human increase in potassium excretion when the administration of cortisol is continued. It is not necessarily accompanied by a

decrease in sodium excretion. The effect of aldosterone on the human increase in potassium excretion is probably due to a release of potassium from the tissues.

Desaulles That is my opinion too.

Fourman What strikes me is that pharmacologists are mistaken as long as they equate these end effects of excretion of sodium and potassium, and as long as they speak about the alteration in Na/K ratio and use this as a measure of aldosterone effect. I think the early effect of

aldosterone is a cellular effect, the other is an effect on the cellular.

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THE EFFECT OF AGE ON THE ELECTROLYTES IN THE RED BLOOD CELLS OF DIFFERENT SPECIES

M J KÄRVÖNEN

*Department of Physiology Institute of Occupational Health,
Helsinki*

Two kinds of age changes may occur in the red blood cells. The erythrocytes themselves have a definite length of life which may be determined in various ways, whereas the longevity of "fixed" tissue cells generally cannot be as exactly indicated. Thus, as cells erythrocytes may be "young" or "old". On the other hand, like any other cells of the body, the red cells may be a part of a young or of an old organism.

Cellular age

In order to study age changes in the erythrocytes as cells, two principal ways are open. One of them is to produce anaemia, e.g. by bleeding, and thus to stimulate erythropoiesis so that a large proportion of the circulating cells will have been produced within a relatively short period. The writer is not aware of any systematic study of the red cell electrolytes throughout the regeneration after acute bleeding. In microcytic anaemias of man—which is the type seen also in bleeding anaemia—the concentration of potassium in erythrocytes is lower than normal (Maizels, 1936). In other types of anaemia a change in the opposite direction may occur (Maizels, 1936, Selwyn and Dacie, 1954, McCance and Widdowson, 1956). However changes in the electrolytes observed in any type of anaemia are not necessarily dependent on the age of the erythrocytes, but may be caused by many other factors associated with anaemia.

Desaulles. That is a very important point, because it is very well known that if responsiveness the following r and other similar experiments, and at different periods after castration we tested the sensitivity of their sexual adnexa. We observed that what was found by Parkes and Deanesley about 20 years ago is still absolutely valid. You must begin the experiments between two and three weeks after castration, after that the sensitivity diminishes very rapidly. If you wait from one to three months some responses disappear completely, and you need very high dosages of the substance to obtain

but not entirely removed by castration

the red cell electrolytes may change with age. The subject was taken up by Hallman and Karvonen (1949) in another species, sheep. A distinct difference between foetal and adult Finnish sheep was observed, in the sense that the concentration of potassium in erythrocytes was higher in foetal than in adult sheep. Fig. 1 shows the differences in both

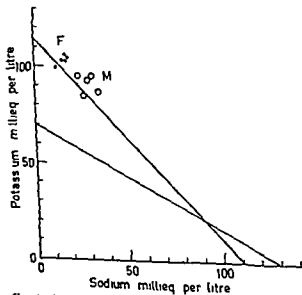


FIG. 1. The concentration of potassium and sodium in erythrocytes of foetal and adult Finnish sheep.

sodium and potassium concentrations. The sum of the two electrolytes tends to remain constant with age.

Widdas (1954) confirmed this observation and found a gradual decrease of the potassium and an increase of the sodium with advancing foetal age.

The study by Hallman and Karvonen (1949) brought out another interesting finding. In 1898 Abderhalden published

Recently it has been claimed that other methods for studying young or old erythrocytes might be feasible. According to Borun, Figueroa and Perry (1957) after centrifugation of blood the bottom layer contains the oldest cells, and the surface the youngest ones. An analysis of the different layers has shown that—at least in human adult blood—the packing is closest and the amount of intercellular plasma lowest in the bottom layer, but when the effect of different packing is corrected there is no difference between the sodium and potassium concentrations of the bottom and the surface erythrocytes (Leppanen personal communication). Serial osmotic haemolysis has also been suggested as a means for differentiating young and old erythrocytes (Simon and Topper, 1957). The value of these methods is not yet clear. However, the nature of the methods used suggests that changes in the electrolyte metabolism of the erythrocytes may be involved in their ageing though such changes may not necessarily result in differences in the concentration of sodium and potassium.

Age of the animal

As a mixed population of different cellular ages erythrocytes are easily available. The availability and development of flame photometric analysis have been a stimulus for several investigations of the electrolyte content of the red cells. It has been found that in general the sodium and potassium content of the erythrocytes in vivo is fairly stable, typical of the species, and resistant to many physiological and pharmacological agents. However in disease particularly in febrile states, erythrocytes tend to lose potassium and gain sodium. In other words, the electrolyte composition of the erythrocytes moves closer to that of plasma.

Sheep and other ruminants It may be inferred from results published by Green and Macaskill (1928) and by Wise and co-workers (1947) that the intracellular potassium concentration is higher in the blood of young calves than in that of adult cattle. These two papers were the first to indicate that

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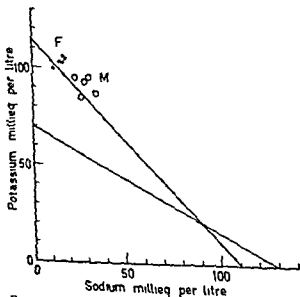


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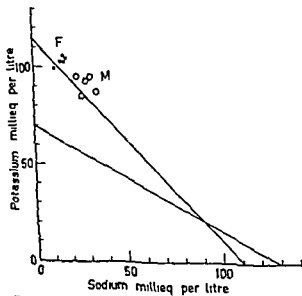


FIG 1 The concentration of sodium and potassium in erythrocytes belonging to foetal (F) and adult (M) Finnish sheep (Hallman and Karvonen, 1949). The concentration of sodium and potassium in erythrocytes of adult sheep is lower than in foetal sheep.

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the first values for the sodium and potassium concentration of adult sheep erythrocytes, and found that they belong to the "low potassium—high sodium" type. In 1937 Kerr observed higher potassium concentrations, with a large variation between individual sheep. In the determinations of Hallman and Karvonen, the erythrocytes of the Finnish sheep turned out to be—contrary to those of Abderhalden—of the "high potassium—low sodium" type, containing still more potassium than the red cells of Kerr's sheep. Sheep erythrocytes thus show a large range of individual variations in the electrolyte composition.

The electrolytes are not the only constituents of the red cells in which individual sheep differ. The solubility characteristics of sheep haemoglobin obtained from different countries, from different breeds, or from different sheep may also differ (Karvonen, 1949, Karvonen and Leppänen, 1952). It was natural, as a working hypothesis, to connect with each other these differences in the red cell electrolytes and in the type of haemoglobin. In the first five samples representing different breeds of sheep, haemoglobin prepared from the low potassium erythrocytes actually showed a crystal habit different from that of the high potassium cells (Karvonen and Leppanen, 1952).

Since these early attempts the red cell electrolytes of sheep have become the subject of intense study. The individual differences in the electrolyte composition have been shown to be permanent characteristics (Evans, 1957). The occurrence of different types of red cells in a number of breeds has been studied, and the genetics of the inheritance have been worked out (Evans, 1954, 1957, Evans and King, 1955. Evans *et al.*, 1956, Evans and Mounib, 1957).

The application of paper electrophoresis to sheep haemoglobins has shown that though there is a definite association between the electrolytes in the red cells and the haemoglobin, this association is not absolute (Harris and Warren, 1955, Evans *et al.*, 1956, Evans, Harris and Warren). On the other hand, the haemoglobin present in the red blood cells has an

influence on the concentration of potassium in the whole blood of both high potassium and low potassium sheep, and thus presumably also on the concentration of potassium in the cells themselves (Evans *et al*, 1956).

The study of individual differences between adult sheep thus shows that the type of haemoglobin is associated with the red cell electrolytes, but that other factors also play a rôle

Haemoglobin changes with age the haemoglobin of a foetus differs from that of an adult in that it is a

with that of younger animals (Karvonen, unpublished)

The transition from foetal to adult life involves a change of In sheep, these and to be compared with those of man (Hallman and 19, Hallman and the changes are exactly parallel would be a subject of considerable theoretical interest

Other species The effect of age on the electrolyte concentration of red cells has been studied in few other species. Remarkably enough, a relationship just opposite to that in ruminants has been found: the sodium concentration is higher and the potassium concentration the same or lower in foetal than in adult erythrocytes, at least in man (Hallman, Österlund and Vora, 1954, Österlund, 1955, McCance and Widdowson, 1956), pig (McCance and Widdowson, 1956), and in guinea pig (Widdas, 1954, 1955, Karvonen and Leppänen, unpublished). The concentration of chloride changes in the same direction as that of sodium.

Underlying mechanisms

It has been pointed out by Conway (1957) that the smaller a cell, the more work per unit cell volume a "sodium pump" must do in the same environment of plasma or extracellular fluid, in order to keep the intracellular sodium at constant

level. A similar conclusion applies to an eventual "potassium pump". The erythrocytes of a foetus are larger than those of an adult. With constant activity of the electrolyte pumps an increase in the cell sodium and a decrease in potassium would be expected from foetal to adult life. This is the direction of development in the ruminants, but not in the other species examined. It is rather questionable whether the decrease in cell size even in the ruminants is an important cause of the changes of the red cell electrolytes.

With the aid of *in vitro* studies much progress has been made in elucidating the mechanism of cation transfer across the red cell membrane. The application of these methods to the erythrocytes of the foetus suffers from a serious limitation: the cells of foetuses (at least human and sheep) haemolyse spontaneously and rather fast *in vitro*. To some extent the rate of haemolysis is dependent on oxygen tension, high oxygen tension increasing the rate of haemolysis, but haemolysis also occurs at an appreciable rate in blood exposed to nitrogen. Haemolysis in human cord blood may also be retarded by administering ascorbic acid to the mothers before delivery, but even so the rate of spontaneous haemolysis remains considerably higher than in adult blood. An addition of ascorbic acid *in vitro* is without effect (Raihä, 1956, and personal communication).

Summary

Information on changes in the electrolyte metabolism of individual erythrocytes during their life cycle is meagre. However, the claims that young and old cells may be separated with the aid of centrifugation or serial haemolysis suggest that changes in the electrolyte metabolism may be involved in the ageing of the red cells. Differences in the actual sodium and potassium concentrations have not, however, been demonstrated.

In sheep and cattle the erythrocytes of a foetus contain more potassium and less sodium than those of an adult. In man, pig and guinea pig a difference in the opposite direction

level. A similar conclusion applies to an eventual "potassium pump". The erythrocytes of a foetus are larger than those of an adult. With constant activity of the electrolyte pumps an increase in the cell sodium and a decrease in potassium would be expected from foetal to adult life. Thus is the direction of development in the ruminants, but not in the other species examined. It is rather questionable whether the decrease in cell size even in the ruminants is an important cause of the changes of the red cell electrolytes.

With the aid of *in vitro* studies much progress has been made in elucidating the mechanism of cation transfer across the red cell membrane. The application of these methods to the erythrocytes of the foetus suffers from a serious limitation: the cells of foetuses (at least human and sheep) haemolyse spontaneously and rather fast *in vitro*. To some extent the rate of haemolysis is dependent on oxygen tension, high oxygen tension increasing the rate of haemolysis, but haemolysis also occurs at an appreciable rate in blood exposed to nitrogen. Haemolysis in human cord blood may also be retarded by administering ascorbic acid to the mothers before delivery, but even so the rate of spontaneous haemolysis remains considerably higher than in adult blood. An addition of ascorbic acid *in vitro* is without effect (Rauhä, 1956, and personal communication).

Summary

Information on changes in the electrolyte metabolism of individual erythrocytes during their life cycle is meagre. However, the claims that young and old cells may be separated with the aid of centrifugation or serial haemolysis suggest that changes in the electrolyte metabolism may be involved in the ageing of the red cells. Differences in the actual sodium and potassium concentrations have not, however, been demonstrated.

In sheep and cattle the erythrocytes of a foetus contain more potassium and less sodium than those of an adult. In man, pig and guinea pig, a difference in the opposite direction

deer? Deer may have sickle cells, and thus is correlated with a certain type of different haemoglobin.

Davson: I know the camel has ellipsoidal cells.

Bull: Is anything known about the relative efficiency of the different kinds of red cells with respect to their function of carrying oxygen, in

Chairman: Dr. Davson, can you comment upon the genetic side of this? You spoke about the sodium pump, what about the difference in haemoglobin?

Davson: I cannot relate this at all. I do not see why a given type of haemoglobin should be associated with a given electrolyte content.

DISCUSSION

reticulocyte or an erythrocyte it loses the power of accumulation of
has only an anaerobic source of metabolism

usually has a very definite cause and is usually due to the fact that the permeability of the membrane becomes abnormally high and you get this Donnan difference of osmotic pressure being exerted between the plasma and the contents of the cell. Therefore, the most profitable line of research would be to try and get conditions in which you could prevent this haemolysis from occurring.

Milne Is there any data available on the foetal levels in the cat and the dog, which have this very high sodium content in the erythrocytes?

Karttunen No, we have none

Dawson The sheep can have as high a sodium content as the cat, yet
a qualitative idea of the content

Karttunen That would be a very interesting thing to do

absolute

absolute

with low

different

slightly

Desautels

Has not the same effect been described for some kind of

THE DEVELOPMENT OF ACID-BASE CONTROL

E M WIDDOWSON and R A McCANCE

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University of Cambridge*

General Principles (as they apply to adults)

When the body of a healthy person is provided with the diet normally eaten in Europe and the United States, it produces in its metabolism more non volatile anions than cations. These "surplus anions" are excreted by the kidney partly in combination with titratable hydrogen ions (the titratable acidity) and partly as ammonium salts. The ammonium salts usually account for rather more than 50 per cent of the total. If the excess of non volatile anions increases, the pH of the urine falls and the titratable acidity increases, but the excretion of ammonia also increases because a fall in the pH of the urine is one of the things which raises the output of ammonia and consequently the percentage of the surplus anions excreted as ammonium salts remains about the same. The excretion of ammonium salts is also increased (a) if the pH of the urine is maintained at its lower limits for some time by the continuous administration of acid or acid forming drugs, and (b) by an increase in the activity of the enzyme which catalyse the formation of ammonia and particularly glutamine dehydrogenase (Davies and Yudkin 1952). (b) By an increase in the acid "load" (Rector, Seldin and Copenhagen 1955). Both (a) and (b) increase the percentage of the surplus anions excreted as ammonium salts and good examples of the effects which may be observed after continuous high dosage are given by Ryberg (1948). As the pH of the urine rises progressively above 6.5 the percentage of the total output of surplus non volatile anions excreted as ammonium salts may also rise and ultimately

Black On the genetic side it is very odd that one gets this scatter right along the line. One would think that, according to Mendel, one would get segregation at the two ends of the line.

I was not clear whether there was an excess of fluid in the red cells. In other words, in the foetal sheep or man was there an excess of potassium per litre of red cells? Was there any difference in phosphate content? Differences in phosphate content have been described, I think by Prinkard (1935 (*Am. Sci.* 14, 931)) and others in connexion with the sickle cell problem, and I wondered whether that side had been gone into with foetal versus grown up sheep.

Karvonen I am afraid I gave a wrong impression when I said the scatter was all along that line. There is a very clear concentration at each end of the line but there is also a group in between. Within each group, however, there is quite a considerable scatter which is due to a permanent individual characteristic of each sheep. The statisticians say that there is quite a high intra individual correlation.

The foetal cells contain more water than the adult cells. In sheep I do not think that any determinations of the phosphate have been done but in man and in pig it has been found (McLance and Widdowson 1936) that the phosphate of the foetal cells is higher.

Dixon It must be realized that when red blood cells are analysed, very large numbers are used: there may well be differences in concentrations of potassium and sodium amongst the individual ones, and they could well fall into groups which would never be discovered. Variations in the Na/K ratio could be reflections of variations in the proportions of high potassium and low potassium cells, which would give a continuous scatter right along the line.

on four additional babies on the 7th to 8th day. Of the seven babies investigated one week after birth, six were breastfed and the seventh was fed on Ostermilk. Samples of blood have been taken from the cord at birth, and from the femoral vein at 48 hours and seven days. Urine has also been collected for 24 hours from one child aged eight months and from one aged one year, while six normal men and women have provided 24 hour urine collections to serve as the adult comparisons. The urines were collected and stored under toluene. Determinations of pH, titratable acid, ammonia, creatinine, phosphate, citrate and sulphate have been made on the urine, and the sera have been analysed for creatinine, CO_2 , chloride, sodium and potassium.

The excretion of surplus anions

Fig. 1 shows the millimoles of surplus anions not combined with fixed base (i.e. titratable acid plus ammonium salts) excreted by the infants on the first, second and seventh days of life and by the older infants. A figure for the adults is indicated also. All the values are expressed per kg. of body weight per day. The average pH of the adult urine was 6 or a little over, while that of the babies was between 5.5 and 5.8,

that of the adults although the pH of the urine was lower, which would have led one to expect a higher rather than a lower anion excretion. Thus low rate of excretion was quite sufficient to maintain the acid base balance of the body, for the serum CO_2 and chloride did not change. It is to be attributed to the fact that the urine contains very little phosphate or sulphate at this period (McCance and von Finck, 1947 and see later), owing to the small breakdown of tissue protein (McCance and Strangeways, 1954). By the seventh day the babies were taking nearly 500 ml. of breast milk a day, which contained 9.5 g. protein or about 3 g./kg., and they were passing about three times as much urine per kg. of

reach 100, because above pH 6.5 the excretion of titratable acid falls more rapidly than the ammonia and is extinguished before the excretion of ammonia, which continues at a decreasing rate up to pH 8. This tendency of the percentage to rise as the pH of the urine goes above 6.5 is therefore exaggerated if the urines are titrated, as they mostly are nowadays, to pH 7.4 instead of, as at one time, pH 8.

Dihydrogen orthophosphates are the main buffer acids which can be titrated in a normal adult's urine, but this may not be so in disease if there is a great excess of abnormal organic acids of the right buffer strength in the urine, such as β -hydroxybutyric acid or amino acids. Apart from the phosphates and weak organic acids which contribute by their presence to the titratable acidity, the surplus of non-volatile anions in the urine is very largely due to sulphates, derived from the metabolism of protein (Hunt, 1956). Chlorides are generally balanced by the equivalent amount of fixed base unless calcium or ammonium chloride has been taken to produce a chloride acidosis.

The ability of the kidney to excrete hydrogen ions into the tubules, and so to excrete the surplus non-volatile anions in the way described, depends upon the activity of carbonic anhydrase. Since it has been shown experimentally that the degree to which the pH of the urine can be lowered depends upon the activity of the carbonic anhydrase at any given time, it may be that the lower and well-known limit of urinary pH attainable by a normal person is an expression of the activity of his carbonic anhydrase, but this is merely a suggestion at the moment.

The Newborn Period and Later Infancy

Complete collections of urine from three healthy baby boys have been made for the first 48 hours of their lives, and again over the whole of the 7th-8th day. These babies all passed urine at the moment of birth and this was also collected. Urine passed by two other babies at birth has also been included in the series, and a 24-hour collection has been made

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body weight as the adults. Their excretion of surplus anions, sulphates among them, per kg, had reached the adult level although they were still excreting little or no phosphate. The pH of their urine was a little higher than it was on the first two days, and the increased volume may have been one reason for this (McCance and von Finck, 1947, Hungerland, 1957).

At eight months to one year of age the babies excreted more

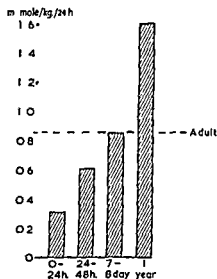


FIG. 1. Surplus anions (not combined with fixed base) excreted by babies during the first week and at 8 months to 1 year of life.

surplus anions per kg of body weight than the adults. This is explainable by the high intake and metabolism of protein per kg of body weight at this time of life. A child of one year consumes about 3.5 g protein per kg, which is two to three times as much as an adult per kg, and only 8 or 10 per cent of it is used for growth in contrast to the 50 per cent or so retained in the neonatal period. The phosphates and the cystine and methionine in the milk and other protein foods were probably the main sources of the surplus anions.

Fig. 2 shows the percentage of the surplus anions excreted with ammonia. For this it is possible to give a figure for urine which was formed *in utero* and passed at the moment of birth and which had a pH of over 6. It will be observed that, although the pH of the urine passed at birth was higher than that of the urine passed afterwards, the percentage of the surplus anions excreted with ammonia was also very high before birth, and of the order to be expected in adults with

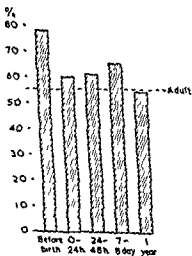


FIG. 2 Percentage of the surplus anions excreted as ammonium salts.

very acid urines after taking large doses of ammonium chloride for some days. The percentage of the surplus anions excreted with ammonia in the first 48 hours and on the seventh day of life has also tended in our series to be higher than that in the urine passed by adults. This is probably because the babies' urine contained so little phosphate, and consequently the titratable acidity was low in relation to the total amount of surplus anions. of it

body weight as the adults. Their excretion of surplus anions, sulphates among them, per kg., had reached the adult level although they were still excreting little or no phosphate. The pH of their urine was a little higher than it was on the first two days, and the increased volume may have been one reason for this (McCance and von Finck, 1947; Hungerland, 1957).

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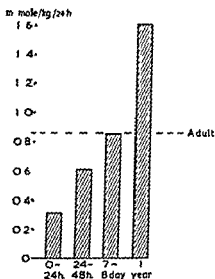


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it is evidently lower even than the excretion of ammonia. By one year of age the glomerular filtration rate/kg had risen above that of adults (McCance and Widdowson, 1952), and more ammonia and surplus amino acids per kg were being excreted (see Figs 1 and 3), the amount of ammonia excreted per ml of glomerular filtrate was near the adult level.

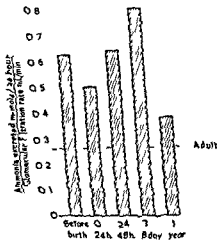


Fig. 4 The ratio of the ammonia excreted (mmole/24 h) to the glomerular filtration rate (ml/min)

The nature of the titratable acidity

Fig. 5 shows the excretion of titratable acid per kg of body weight by the babies and the adults. The amount excreted was low during the whole of the first week, but it was rising even though the urine still contained no phosphates. The high excretion at a year is again related to the high intake of protein at that age.

Fig. 6 shows the percentage of the titratable acidity due to phosphate in the urine of an adult and in the urine of a breast fed baby in the first week of life. In the adult the percentage depends upon the pH and, since the pH of the urine passed

which has been done on kidney slices *in vitro* (Robinson, 1954), and on renal glutaminase and ammonia production (Hines and McCance, 1954) goes to show that, weight for weight, the kidney of the newborn of other species contains less glutaminase and produces less ammonia than that of the adult. Fig 3 shows that the total amount of ammonia excreted per kg of body weight was in fact small in the first two days, but that by a week, when the baby was taking in three times as much protein as the adult per kg of body weight, it had risen above the adult level. The ability to form ammonia in response to an acid load in the first day or two of life has not yet been

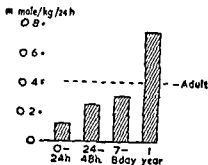


FIG 3 The amount of ammonia excreted

studied in man, but Cort and McCance (1954) found it to be smaller in puppies two days old than in adult dogs. The matter requires further investigation.

Fig 4 shows the excretion of ammonia in millimoles/24 hours divided by the glomerular filtration rate (as measured by the endogenous creatinine clearance) in ml/minute. It was possible to calculate this ratio for the urine passed at birth, even though the rate of urine flow before birth was not known, because the two functions being compared are both expressed in terms of rates of urine secretion. The excretion of ammonia was high *in utero* and in the newborn period in relation to glomerular filtration rate. The glomerular filtration rate at this time of life is very low by adult standards, and if the endogenous creatinine clearance is a true measure of it,

more than the amount excreted by the adults in this series and so far as citric acid may be regarded as a product of the metabolism of the kidney it cannot be classed as a surplus ion although it contributes to the titratable acidity.

It is well known that infants on cows' milk mixtures have a higher concentration of inorganic phosphorus in their serum than breastfed infants, they excrete phosphates by the seventh day of life, and the phosphate organic acid relation ship is of the adult pattern, as it is also in the urine of infants eight months to one year of age

Foetal Life

In the uterus the acid base balance of the whole conceptus is regulated ultimately by the mother's lungs and kidneys, but the foetal kidneys, membranes and placenta act as intermediaries

Urine has been taken from the bladders of five human foetuses aged 10-20 weeks. It has always been found to be hypotonic, due mainly to very low concentrations of sodium and chloride. It appears to resemble the urine formed *in utero* and passed at term which has been better investigated and described elsewhere (McCance and Widdowson, 1953, Hanon, Coquoin Carnot and Pignard, 1955, 1957)

The pig has a gestation period of about 120 days. Between the 20th and 60th day there is a rapid expansion in the volume of allantoic fluid. The sac containing the fluid has free connexion with the kidney through the urachus and bladder. Its membranes also participate in exchanges with the mother. Table I shows the composition of the fluid at 20 days, 45 days and 60 days. At 45 days both mesonephros and metanephros are functional, but the former is becoming less so. The

... falls greatly so that from 45 days it is only one half or one third that of foetal serum (McCance and Dickerson, 1957). This fall in osmolar concentration is due largely to a fall in the concentration of sodium and chloride. The

by the present series of adults was higher than that of the newborn infants, the value for adults shown in Fig 6 (70-80 per cent) has been taken from Gamble (1942). Phosphates accounted for a very small fraction of the titratable acidity of

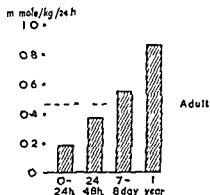


FIG 5 The excretion of titratable acid

the infant's urine, which is due to the fact, already mentioned, that the urine of breastfed infants contains so little phosphate at this time of life.

Investigations are being made on the organic acids in the

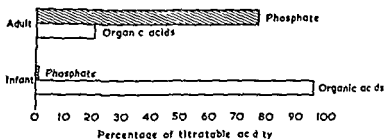


FIG 6 The proportion of titratable acid due to phosphates and organic acids in the urine (pH 5.5-6.0) of adults and infants

urine during the first week of life. Citric acid is one of the major constituents, and on the seventh day the breastfed babies were found to be excreting 33 mg citrate/kg body weight/24 hours (Stanier, personal communication). This

hoped to extend the study to later stages of gestation, to other membranes and to glutaminase.

before birth, or whether the fluid has been made hypotonic and acid by the action of the membranes themselves. Small amounts of fluid have been removed from the bladders of foetuses at 45 days and it is probably possible also to withdraw fluid from the large mesonephric duct, so that this problem may be soluble without recourse to large scale experimental veterinary obstetrics. Should it turn out that the composition of the fluid is being altered by the membranes, their activities may contribute materially to our ideas about the function of the renal tubules.

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concentration of potassium does not fall in the same way, and the concentration of calcium rises. This calcium appears to be held in solution by citric acid (Economou Mavrou and McCance, 1958).

The fluid at 45 days has been found to have a pH between 5.5 and 6, and a titratable acidity of about 10 m-equiv/litre. The fluid contains ammonia and ammonia appears to account for about 25 per cent of the titratable acid plus ammonia found in it. The concentration of phosphates is always small, and the acidity is almost entirely due to carbonic acid. The

Table I

THE WEIGHT OF THE FOETAL FIG AND THE VOLUME AND COMPOSITION OF ITS ALLANTOIC FLUID

| Foetal age | 20 days | 45 days | 60 days |
|---------------------------------------|---------|---------|---------|
| Weight of foetus | 0.1 g | 20 g | 100 g |
| Volume of allantoic fluid | 5 ml | 110 ml | 350 ml |
| <i>Composition of allantoic fluid</i> | | | |
| Osmolar concentration m-osm/l | 256 | 120 | 92 |
| Urea m-mole/l | 3.1 | 8.4 | 10.3 |
| Chloride m-equiv/l | 69 | 30 | 18 |
| Sodium | 114 | 13 | 14 |
| Potassium | 14 | 8 | 6 |
| Calcium mg/100 ml | 6 | 30 | — |
| Inorganic phosphorus mg/100 ml | 9 | 6 | — |

pH rises quickly if the fluid is shaken or even if it is left in a tube exposed to the air, and it was found necessary to collect and analyse the fluid out of contact with air. Lutwak Mann and Laser (1954) found no "bicarbonate" in pig's allantoic fluid at 20 days' gestation but there is no doubt about the presence of carbonic acid at 45 days.

Further investigation has confirmed the fact, first noted by Lutwak Mann (1955), that the chorioallantoic membrane contains carbonic anhydrase. At 45 days the allantoic fluid itself also had some carbonic anhydrase activity. On the basis of material from three pregnant pigs the activities of carbonic anhydrase may be given as foetal kidney + + +, chorioallantoic membrane + +, allantoic fluid +. It is

the major organic acid constituent of the urine which is passed immediately after birth. In addition urine passed during the first 24 hours of life contains malic acid, glycolic, lactic, β hydroxybutyric, succinic, and α ketoglutaric acids, but not aconitic acid. With this method one can detect a minimum of 20 μ g of each of these organic acids.

Adolph: Is there any appreciable accumulation of organic acids in the newborn during the first week of life? At this stage the individual is very insensitive to the hydrogen ion concentration changes as far as the breathing is concerned and I was wondering whether it is also insensitive as far as excretion is concerned.

Zareymuller: We are now working on the detection and identification of the organic acids found in the urine of normal newborn babies and the next problem will be to identify those found in the urine of hypoxaemic newborn babies.

Karvonen: Did you find any pyruvate or does it come out with this method?

Zareymuller: We have not found a pyruvic acid spot, but we have not added pyruvic acid to the urine so we do not know exactly where the spot should appear on the paper.

Karvonen: I understand that increased excretion of pyruvate has been found during the first few days of life (Tallqvist H (1952) Thesis, Hameenlinna).

Zareymuller: There is an interesting paper about some work on the output of organic acids in potassium depletion in which pyruvic acid, lactic acid, α ketoglutaric acid and citric acid were estimated but this was done on normal adults (Evans et al (1957) Clin Sci, 16, 53).

Faurman: The hydrogen ion in the allantoinic sac must come from somewhere; it cannot be manufactured. It must come in the end from the mother and since she cannot manufacture the hydrogen ion it must ultimately come from her diet. So what happens if you feed alkali to the mother pig?

Widdowson: We have not tried that.

Milne: It is well shown in your paper, Dr Widdowson, how the newborn baby copes with its normal environment. I would agree that the organic acid level, especially that of citrate, is proportionally much higher than in the adult. Obviously in assessing the efficiency of the kidney, particularly in excreting an acid load, one must give it a maximum challenge and though I see the difficulties of this in human experimentation it would be extremely interesting to do this in the newborn animal. There seem to be two separate aspects of excretion of acid by the kidney. One is the ability of the kidney to excrete a maximum amount of hydrogen ion per day and clearly that can only be assessed by giving a prolonged acid load. The other is the ability of the kidney to maintain a hydrogen ion gradient between urine and plasma, in other words the production of a minimum urinary pH. I would be very interested in having data on whether the minimum pH of adult urine is similar to the minimum pH of newborn urine, whether the ammonia excretion can increase on prolonged acid ingestion proportionally to that of the adult,

DISCUSSION

Zweymüller. The identification of organic acids in urine by paper

Nordmann and co-workers (1954 *C.R. Acad Sci, Paris*, 238, 2459), and Fig 1 demonstrates the position on a two-dimensional descending chromatogram of some non volatile, water soluble organic acids which

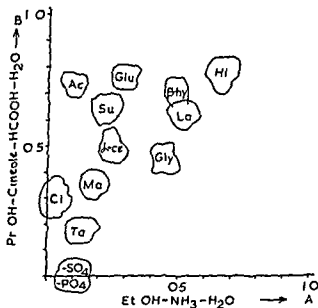


Fig 1 (Zweymüller) The position of some organic acids in the urine of a normal adult on a two dimensional descending chromatogram

Cl = Citric acid, Ta = Tartaric, Ma = Malic
 Gly = Glycolic, αce = α ketoglutaric, Su = Succinic,
 Ac = Aconitic, Glu = Glutaric βhy = β hydroxy-
 butyric, La = Lactic, Hi = Hippuric

injections

McCance The lower limits might be due to the activity of carbonic anhydrase having a ceiling in the human kidney. We know that if the carbonic anhydrase is defective the lowering of pH is correspondingly limited.

and finally whether this very large citrate output in the newborn shows the same tremendous lability to acid base effect as it does in the adult, in whom it can be reduced by quite small doses of acid or increased by alkalization, say by sodium bicarbonate

Widdowson. We have not yet given an acid load to newborn babies,

The difficulty in an animal which is developing very rapidly is to separate the effects of several days' administration of an acid forming drug and

altering the pH of the urine upon the excretion of citrates in the newborn baby.

Scribner. We carried out some experiments in rats which seem to indicate that the amount of citrate in the urine depends on the kidney tissue level of citrate rather than on the blood citrate level. After intraperitoneal injection of citrate increases 10- to 20 fold increases two to threefold. I response to intraperitoneal

the blood level rises nearly 100 per cent, but there is little or no increase in either kidney tissue citrate or urinary citrate. We concluded from these experiments that the level of citrate in the urine under these conditions is determined by the citrate level in the renal tubular cell and is independent of the amount of citrate filtered through the glomerulus.

McCance. Dr. Milne, what determines the lower limits of pH which the human and other kidneys can achieve?

Milne. I think this can only be answered conditionally. First, one must state the stimulus, and secondly one must state the conditions of the kidney at that moment. Ammonium chloride has been used as the usual stimulus and I think no one has ever produced a pH of human urine below 4.4 by that method, but other stimuli seem able to produce a considerably lower pH. The experiments of Schwartz, Jenson and

(1957) showed that when they infused clearly, stimulus

plus, and indeed this agrees in the rat. It is very difficult to produce a highly acid urine in rats by most experiments. When it is given ammonium chloride the rat seems to be able to keep up with the ammonium intake and puts out ammonium chloride in its urine almost as quickly as it is either injected or taken in the drinking water. But an

have not shown a potassium deficiency as in muscle, but they have shown a fall in intracellular bicarbonate and therefore presumably a fall in intracellular pH. These experiments have not, as far as I

possibly greater

look the histological structure in Prof. Wallace's potassium deficient animal. It seems —

looking muscle fibres in Prof. Wallace's animal than we see in the control animal.

Young animals were presumed to look frayed and woebegone. Subsequent experiments showed that dietary deficiencies and alterations could produce similar changes in the muscle of older and younger animals in the young result of

basic questions of what is adequate nutrition of a cell and how can it be maintained.

Wallace: What is old and what is young? — quite young while

Shack: To me a when I talk of an least is at an age

Wallace: Young logical changes in muscle. These changes can be almost completely reversed in as little as 36–48 hours after potassium administration. The lesions in cardiac muscle do not show this rapid type of healing. It would be interesting to see if your old rats have a slower repair time. Dr. Hungerty has already mentioned that older rats chemically repair potassium deficiency more slowly than do the young ones.

GENERAL DISCUSSION

Wallace: I should like to present a problem that arises when one attempts to interpret chemical analysis of tissues from deficient animals in terms of histological appearance. Skeletal muscle taken from potassium-deficient animals is low in potassium, high in sodium, high in its content of basic amino acids and probably low in bicarbonate content. When the muscle is examined histologically one sees apparently normal cells lying side by side with grossly abnormal cells. Which cells account for the chemical abnormalities? I have wondered if a cell can tolerate any deficit at all. Possibly, for the cell, it is an all-or-none phenomenon. Does a tissue as a whole become deficient in a sort of quantum fashion, cell by cell rather than by an over-all shared process by all of the cells? Is it not necessary to get down to a truly cellular level to further our understanding?

Fourman: May I add to Prof. Wallace's problem? The kidney and the heart show the morphological changes of potassium deficiency before the other tissues. These two tissues, when they are analysed in animals that have been made deficient in potassium, do not as a rule show chemical evidence of potassium deficiency. I suppose they do if you carry the deficiency far enough but as a rule they do not. It has always been a puzzle to me why two tissues that have a normal potassium content are the first tissues to show a potassium abnormality. These two tissues are also ones that never rest, in the way muscles do, and one wonders whether the fact that their function requires the maintenance of a normal potassium content, with the demand on the metabolic energy of the cell that this entails, carries the seeds of their own destruction.

Wallace: The analyses of Orent-Keiles and McCollum do show deficits of potassium in cardiac muscle taken from deficient rats (1941. *J. biol. Chem.*, 140, 337). However, most workers have not shown the same thing.

Black: Jean Oliver and co-workers (1957 *J. exp. Med.*, 106, 563) have done work on the localization of the morphological defect in the nephron of potassium depleted animals, and this seems to be limited to the proximal and the collecting tubules. Dr. Fourman's difficulty may not be so real if the lesion is as sharply localized as that. With analysis of the whole kidney that may just be a failure to detect a limited local deficiency of potassium.

Milne: Part of the difficulty may be this, is not the necrosis or degeneration in the cell possibly due to the fall in intracellular pH, not primarily to potassium deficiency? I agree that kidney analyses

have not shown a potassium deficiency as in muscle, but they have shown a fall in intracellular bicarbonate, and therefore presumably a fall in intracellular pH. This is presumably not as far as I

possibly greater

Fourman Yes, unless you think as I did, that the fall in intracellular pH is a result of the fall in intracellular potassium

has prepared from our material, which show a reduction in potassium content of the total muscle mass. There were fewer nice looking muscle fibres in Prof. Wallace's animal than we see in the

who there was quite a flurry about the electron microscopic studies of mitochondria. In such pictures the mitochondria from cells of old animals were presumed to look frayed and woebegone. Subsequent experiments showed that dietary deficiencies and alterations could produce similar changes in the mitochondria taken from cells of young animals. If the few cellular changes we can observe in older animals can be produced by nutritional and dietary alterations in the young ones, it is possible that these 'age changes' are the result of chronic malnutrition of the cells. This brings us to the basic questions of what is adequate nutrition of a cell, and how can it be maintained.

Wallace What is old and what is young? To me it is quite your

Shock
when I take
least is at

Wallace . . . how much potassium-deficient do show morphological changes in skeletal muscle. These changes can be almost completely reversed in as little as 36-48 hours after potassium administration. The lesions in cardiac muscle do not show this rapid type of healing. It would be interesting to see if your old rats have a slower repair time. Dr. Hingerty has already mentioned that older rats chemically repair potassium deficiency more slowly than do the young ones.

Kennedy, *Morrison* and *Gordon* (1957. *Fed Proc*, 16, 366, and personal communication) have reported that a 24 month old rat starved of food but not water for 24 hours loses far more urea, creatinine and potassium than a young one of comparable weight. So there is a state of incipient potassium deficiency. We have also found that the adrenals are a little bigger in these old rats.

al, (1952). *J. Geront*, 7, 351; *Bogdonoff et al*, (1953, 1954) *J. Geront*, 8, 272; 9, 262, *Watkin et al*, (1955) *J. Geront*, 10, 268). We consistently found that the older individuals, when given good protein intakes that resulted in positive nitrogen balances, retained potassium in excess of the theoretical amount required for the nitrogen retained. A good deal of this, I am sure, may be due to cumulative analytical errors, but it has always seemed to me that the older animal will work himself into a potassium deficiency if given the opportunity.

Black. Is not some of our difficulty here due to the limitations of morphology? If we take as our criteria of morphological change the

how we can expect morphology to decide its aetiology.

Talbot. When you use the term 'potassium deficient', Prof *Wallace*, do you wish us to think simultaneously about the correlated fact of the cellular sodium excess? Cellular sodium intoxication may actually be the provocative factor under some circumstances.

Wallace. Sodium excess is usually a corollary but not always. Some cation, it would seem, must replace the deficit. Basic amino acids have been shown to increase in potassium deficient tissues as well as sodium.

Talbot. We have just done some experiments where the absolute

an light in our hands. Some of

by your work (*Conway*, E. J., and *Hingerty*, D. J. (1948) *Biochem J*, 42, 372). Unlike you we found that sodium was lost simultaneously with a gain of muscle

potassium to - -

(1955) *Am*

Stryer T

and other 1

basis or mu

the true sex

the ratio of - - - two sex hormones, or is it in fact due to some characteristic which depends upon the presence of one X or two X chromosomes?

Kennedy It is probably something to do with species, but the differences in size and growth between the castrate cockerel and the castrate hen, and the same sort of thing in male and female castrate rats, are very well known, and there is obviously a genetic difference in the subsequent behaviour of the neonatal castrate. Some of the early theories of ageing depended on body size, and one wonders how much actual size, or organ development and growth as such, rather than sex alone, affects the matter. The kidney of the male castrate rat, even though it is castrated very young, is a much bigger organ and in some senses therefore, is a more developed or older organ than that of a female rat. Purely structural factors may determine some of the differences in what I think you call end-organ responsiveness.

Stryer Is castration even shortly after birth early enough? After all the foetal testis has a very important role to play and intra-uterine castration might avoid this difficulty.

Desaules That might possibly be helpful in determining the role of the X zone. It is hard to imagine how the interrelationship between pituitary, adrenals and gonads acts just at the beginning of life in the animal.

Wilne Is the control to the castrate male a spayed female?

Desaules They are quite different—that is the annoying point.

Kennedy When he discussed renal function Dr Shock pointed out that there was some similarity between the old and the young kidneys in their inability to sustain water diuresis and so on. It has been shown (Smith H (1951) *The Kidney, Structure and Function in Health and Disease* New York: Oxford University Press) that if you take an animal of intermediate age and remove one of its kidneys and half the other then the initial response, at least, is a great diminution in water diuresis which may take four weeks to be restored to about two-thirds normal. This may suggest that the period during which the major changes in the newborn develop is during the unfolding of the anlage of the kidney, senescence in most animals that have been studied similarly involves a loss of structural units. So again, simply the amount of end organ which is there may be the important thing, apart altogether from what is called the endocrine climate.

Kennedy, *Morrison* and *Gordon* (1957. *Fed. Proc.*, 16, 366, and personal communication) have reported that a 24 month old rat starved of food but not water for 24 hours loses far more urea, creatinine and potassium than a young one of comparable weight. So there is a state of potassium deficiency in old rats.

Shoc I have found that the older individuals, when given good protein in takes that resulted in positive nitrogen balances, retained potassium in excess of what was lost. A good deal of errors, but

work himself into a potassium deficiency if given the opportunity.

Black Is not some of our difficulty here due to the limitations of morphology? If we take as our criteria of morphological change the fact that the tissue 'looks bad' or 'looks moth eaten', then we are not going to get anywhere in deciding the cause of this change. You can hardly expect a cell to have a signpost saying 'I am too old', or 'I am potassium deficient'.

Ta Wallace, do you wish us to think simultaneously about the correlated fact of the cellular sodium excess? Cellular sodium intoxication may actually be the provocative factor under some circumstances.

Wallace. Sodium excess is usually a corollary but not always. Some cation, it would seem, must replace the deficit. Basic amino acids have been shown to increase in potassium deficient tissues as well as sodium.

Talbot We have just done some experiments where the absolute

had cellular sodium intoxication that showed all the symptoms commonly considered characteristic of marked potassium deficiency.

Hingerty Prof. Wallace, when you restored the potassium, morphology right in 36 hours. Did you

our work (Conway, E. J., 42, 372). Unlike you we

found that sodium was lost simultaneously with a gain of muscle

THE RÔLE OF THE KIDNEY IN ELECTROLYTE AND WATER REGULATION IN THE AGED

N W SMOCK

*Gerontology Branch National Heart Institute National Institutes
of Health PHS D.H.E. & W Bethesda and the Baltimore City
Hospitals Baltimore Maryland*

THE kidney is the first line of defence in maintaining appropriate concentrations of water and electrolytes in the internal environment of all the cells in the body. Although there are other avenues through which salts and water may be lost from the body, and other factors which may enter into the regulation of concentrations in local areas, it is the kidney which carries the major burden of electrolyte and water regulation. The kidney responds to a multitude of stimuli and is blessed with large reserve capacities. It is the purpose of this report to describe briefly some of our findings with regard to age changes in renal function, to discuss the possible mechanisms of these changes and to discuss their relation to the maintenance of certain physiological constants in the aged.

In order for the kidney to serve its functions of regulating water and electrolyte concentrations, as well as the volume of extracellular fluid, blood must be delivered to it in adequate amounts, glomerular filtrate must be formed, and the tubular cells must selectively reabsorb and excrete substances in accordance with a variety of stimuli to which the kidney must respond. The application of clearance techniques makes it possible to assess the nature of age changes in discrete renal functions. The studies to be reported are based on ambulatory male subjects between the ages of 20 and 90 years who were found to be free from clinical evidence of renal disease as judged by clinical laboratory tests and medical history. All

Adolph · I wish the structural picture agreed so well with the physiological response to water loading. First of all, when you take out one kidney from, say, a middle aged rat, you do not reduce the water diuresis much—it is more often a reduction of 20 per cent than of 50

available, as far as anatomical studies show, is about 50 per cent of that in the adult, and yet the diuresis may only be 10 per cent of the adult's. As the diuresis develops in intensity with age, it gets far

clearances
 is given out

clearances

Desaulles · When a heminephrectomized animal is submitted, eight or ten days after operation, to a physiological saline load of about

is given out

volume which damages certain nephrons in several different ways. The resulting morphology may be very various but the functional

Although there is a substantial variation between subjects at any given age, the trend is highly significant *

The age decrement in glomerular filtration rate, as measured by standard inulin clearance, is shown in Fig 2. The regression of inulin clearance with age is expressed by the equation $Cl_{in} \approx 153.2 - 0.96 \times \text{age (in years)}$. The average decline over the age span 20-90 years was 46 per cent in this instance †

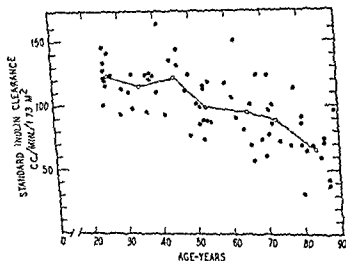


FIG 2 Change in standard inulin clearance or glomerular filtration rate with age. O—O average values ml filtrate/min./1.73 sq m body surface area.

(From Shock 1952)

The fall in glomerular filtration rate is closely associated with the fall in plasma flow so that the filtration fraction, calculated as ratio of inulin clearance to the diodrast clearance, shows only a slight increase with age (Fig 3)

* In a different sample of subjects in whom renal plasma flow was estimated from ¹³¹I (p-aminohippuric acid) clearance (Watkin and Shock 1952) the

subjects were selected only after a thorough history and physical examination which excluded recent or remote renal diseases, cerebrovascular accidents, coronary artery disease, syphilitic or rheumatic heart disease, hypertension, or any recent alterations in body weight. All tests were carried out under basal conditions and subjects were hydrated with 600-800 ml. water, given orally 1-2 hours before the test, and 200 ml. water were given at half hour intervals during the

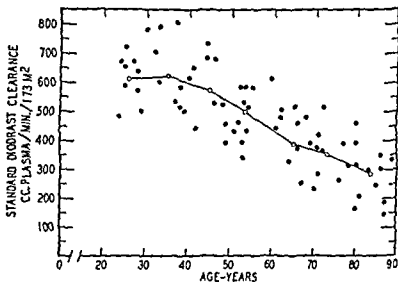


FIG. 1 Change in standard diodrast clearance or effective renal plasma flow with age. ○—○ average values ml plasma/min / 1.73 sq m body surface area (From Shock 1952)

test. The constant infusion method was followed, and four clearance and four T_m periods of 10-14 minutes each were taken according to the method of Smith, Goldring and Chasis (1938). Fig. 1 shows the age change in effective renal plasma flow as estimated from diodrast clearance (Shock, 1952). Between the ages of 20 and 90 years there was a decline in the effective renal plasma flow amounting to approximately 53 per cent. The regression equation relating the diodrast clearance to age is: $Cl_D = 810 - 0.11 \times \text{age (in years)}$.

The maximum capacity of the renal tubule to excrete diodrast also diminishes with age. Fig. 4 illustrates the results of this test in the subjects studied. The average diodrast T_m fell from 54.6 to 30.8 mg iodine/l. 73 m²/min between the ages of 20 and 90 years. This represents a reduction of 43.5 per cent. The regression equation relating diodrast

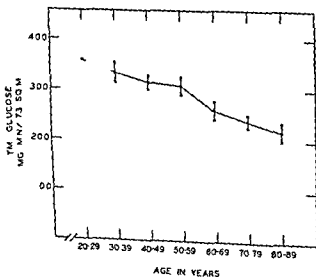


FIG. 5 Decrease in maximal tubular reabsorptive capacity with age. The slope is drawn to connect the mean values for each decade. The vertical lines represent \pm one standard error of the mean while the open circles define the limits of \pm one standard deviation of the distribution.

(From Miller, McDonald and Shock 1952)

T_m to age is $T_{mD} = 80.7 - 0.40 \times \text{age (in years)}$ *. The reabsorptive capacity of the renal tubular epithelium for glucose also shows a comparable diminution with age, as shown in Fig. 5. The average glucose T_m fell from 328 to 223 mg glucose/l. 73 m²/min between the ages of 30 and

* The maximum excretory capacity for PAH shows the following regression on age: $T_{mPAH} = 120.6 - 0.86 \times \text{age}$ (Watkin and Shock 1953)

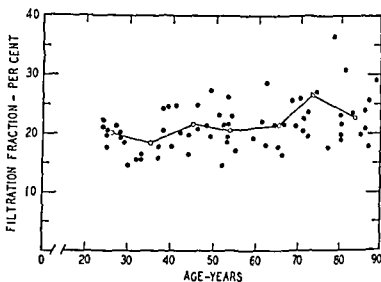


FIG 3. Change in filtration fraction with age \bigcirc — \bigcirc average values, per cent of plasma filtered
(From Shock, 1952)

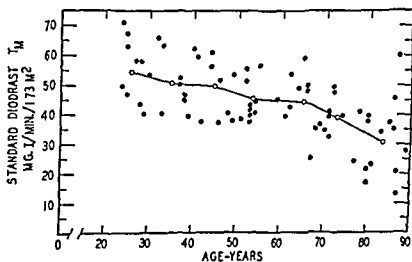


FIG 4 Change in standard diodrast T_m with age \bigcirc — \bigcirc average values mg diodrast iodine/min / 1.73 sq m body surface area.
(From: Shock 1952)

Landowne and Shock, 1955), as shown in Fig 8, a portion of the reduction in renal plasma flow must be attributed to a reduction in total blood flow. However, in experiments to be reported later calculations show that the age reduction in renal blood flow is proportionally greater than the reduction in cardiac output.

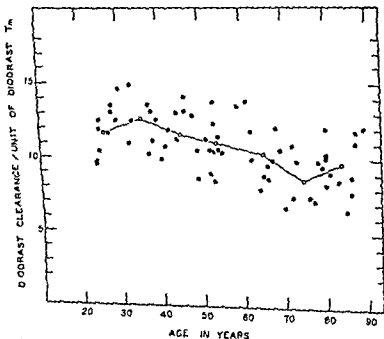


Fig 7 Change in effective renal plasma flow per unit of diodrast Tm

○—○ average values

(From Shock 1952)

Other experiments have shown that the reduction of effective renal plasma flow in the aged cannot be ascribed to permanent structural changes in the renal vascular bed (McDonald, Solomon and Shock, 1951). Previous studies have shown that the administration of a pyrogen to young people

90 years. The regression equation is $Tm_G = 432.8 - 2.604 \times \text{age (in years)}$. The maximum capacity for both a reabsorptive and excretory mechanism in the renal tubules showed approximately the same percentage decrement with age.

The average inulin clearance per unit of Tm remains constant between the ages of 20 and 90 years (Fig. 6). This finding lends support to the hypothesis that a nephron loses its function as a unit. In contrast, the diodrast clearance per

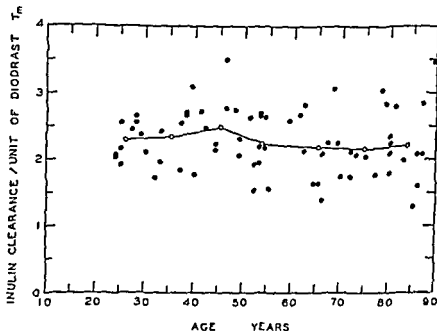


FIG. 6 Change in rate of glomerular filtration per unit of diodrast T_m
 ○—○ average values
 (From Shock 1952)

unit of Tm decreases from an average value of 12.6 at age 30-39 to 9.7 at age 80-89 (Fig. 7). This steady decline in the effective renal plasma flow per unit of tubular excretory capacity indicates that the average amount of blood delivered to each tubule, and by implication each nephron, declines with age. Since we have been able to demonstrate a significant reduction in resting cardiac output with age (Brandsonbrener,

average of 20 subjects in each age group, are shown in Fig. 9. From the three curves at the bottom of the graph, the effect of the pyrogen in

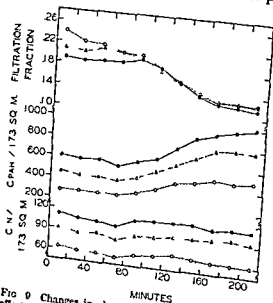


FIG. 9 Changes in glomerular filtration rate (C_N), effective renal plasma flow (C_{PAN}), and filtration fraction during the pyrogen reaction. Fifty million killed typhoid organisms were injected intravenously at 0 time. ○—○ mean values for 14 subjects aged 0-85 years (O group) Δ—Δ mean values for 20 subjects aged 50-69 years (Δ group) ●—● mean values for 20 subjects aged 20-49 years (Y group)

(From McDonald Solomon and Shock, 1951)

either the young, middle, or old subjects. The three curves in the centre of the graph show clearly that, beginning about 80 minutes after the administration of the pyrogen, there was a slow continuous rise in renal plasma flow in all groups of subjects. Although the mean absolute increases were greater for the young than for the old group, where increments were

results in a marked increase in effective renal plasma flow. In order to assess age changes in the ability of the renal vascular bed to dilate, glomerular filtration rate and renal plasma flow

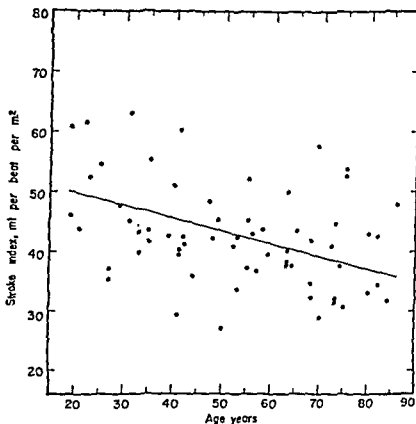


FIG. 8. Stroke output per sq. m. surface area versus age. Each point represents the average of two measurements in 49 subjects, of three measurements in four subjects, and a single measurement in 14 subjects. The line indicates the simple linear regression for the data.

(From: Brandfonbrener, Landowne and Shock, 1955).

were measured in young, middle-aged, and old subjects following the intravenous administration of 50,000,000 killed typhoid organisms (0.5 ml. typhoid-paratyphoid A and B vaccine). The results of these experiments, based on the

flows, oral fluid intake was supplemented by the intravenous administration of 5 per cent dextrose in distilled water, in which appropriate quantities of inulin and sodium amino hippurate had been added at the rate of 8 ml/min by a constant infusion pump. Twenty nine adult males, ranging in age from 26 to 86 years, served as subjects. The total sample was arbitrarily divided into three age groups: young (no = 9, age range from 26-45), middle (no = 10, age range from 46-65) and old (no = 10, age range from 66-86). After three control collection periods, 0.05 milliunits pitressin/kg body weight was administered intravenously. Subsequently, six consecutive urine collections, each of 12 minutes duration, were made. During the control periods, the average urine flow for the young subjects was approximately 14 ml/min, middle aged 11 ml/min and old subjects, 10 ml/min. The urine/plasma (U/P) inulin ratio was calculated as an index of water reabsorption. The results of this experiment are shown in Fig. 10, where the U/P inulin ratio was plotted against the urine collection period. During the control periods the U/P inulin ratios were approximately 10 for all three age groups. Following the administration of pitressin, prompt antidiuresis was noted in all three groups. Peak antidiuresis and peak concentration of inulin were observed in all three age groups during this period which was 12-24 minutes after pitressin. As indicated in Fig. 10, there was a marked age difference in the antidiuretic response to this standard stimulus. The young subjects showed the maximum response and the old subjects showed the minimum. In Fig. 11 the tubular response is shown. C is the concentration of inulin in the urine and the regression of the concentration on age was described as $U/P \text{ inulin} = 162 - 1.6 \times \text{age (in years)}$. Although the administered pitressin resulted in a rise of blood pressure, it averaged only 10 mm at two minutes after injection and fell to control levels within five minutes. These experiments indicate that, in the older individual there is an impairment in the

expressed as percentages of the base line values, the rise in renal blood flow for the young, middle, and old groups was 76, 86, and 91 per cent respectively. As shown by the upper three curves, the filtration fraction diminished markedly in all subjects, indicating a fall in effective filtration pressure, which would result from a greater vasodilatation at the efferent than at the afferent side of the glomerulus if there were no change in blood pressure. Actually, the diastolic blood pressure dropped slightly in the middle and old groups, but remained constant throughout the reaction in the young group. At the height of the reaction the differences in the filtration fraction observed under resting conditions, completely disappeared. The small absolute changes in renal plasma flow in the older subjects following pyrogen, are consistent with the anatomical findings of a progressive decrease in the number of glomeruli in the aged kidney (Moore, 1931). On the other hand the time of onset and the percentage increase in renal plasma flow were similar in the different age groups. Consequently it must be concluded that the responsiveness to pyrogen of the vascular elements remaining in the aged kidney is not qualitatively different from that in the young kidney. It is inferred from these experiments that the renal arterioles in the aged kidney are capable of dilating and that in the resting state there is a functional vasoconstriction of the afferent arterioles in the aged which under resting conditions diverts blood from the kidney to other parts of the circulation.

To function effectively the kidney must respond to a variety of stimuli. One of the most important signals for altering the reabsorption of water by the renal tubule is the antidiuretic hormone. Age differences in the inhibition of water diuresis following the intravenous administration of small amounts of pitressin have been observed (Miller and Shock, 1953). In these experiments a maximum water diuresis was established by the oral administration of 500 ml water at 6 00 a m, followed by 250 ml water at half hour intervals until completion of the test. To ensure maximum urine

of the falling cardiac output. This vasoconstriction is functional in character and can be removed by an appropriate physiological stimulus. Although the tubular epithelium responds to the stimulus of the antidiuretic hormone as quickly in the old as in the young, the functional capacity of the tubular epithelium to perform osmotic work shows a gradual reduction with age.

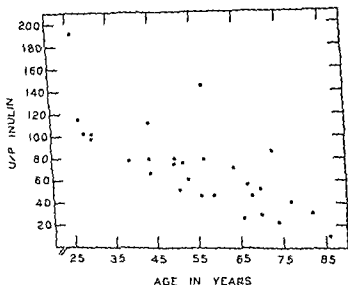


Fig. 11 Relationship between maximum U/P inulin following pitressin, and age. The ordinate is the mean U/P ratio for periods 5 and 6. (From Miller and Shock, 1953)

Although these experiments serve to define certain limitations in renal function with increasing age, we must turn to other observations to tell us how effective the renal function is in the old.

There is no evidence of any systematic changes with age. Although Videbaek and Ackermann (1953) reported a slight rise in plasma potassium concentrations, 4.0–4.5 m-equiv/l, between the ages of 25 and 90, the

functional capacities of the tubular cells to perform osmotic work on the glomerular filtrate

The results of these observations lead to the concept that with increasing age, there is a gradual loss of nephrons in the

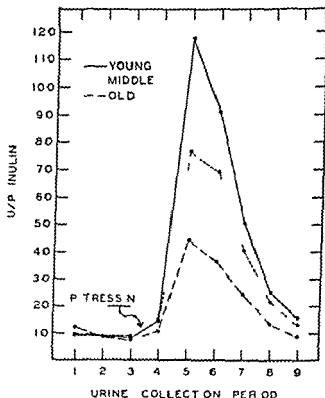
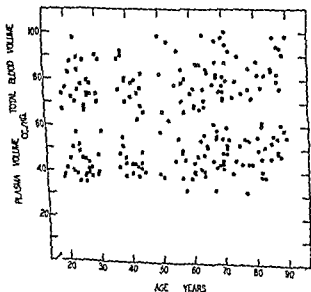


FIG. 10. Mean values of U/P inulin ratio for each of three age groups before and after the intravenous administration of pitressin. Urine collection periods 1-9 represent nine consecutive 12 minute periods. Pitressin was administered immediately after the conclusion of period 3.

(From Miller and Shock, 1953)

kidney. In addition to these structural losses there are functional changes. One of these is a gradual increase in the vasoconstriction of the vascular bed of the kidney which further reduces the flow of blood through it, even in the face

Alving (1938) found some evidence that with increasing age there is an accumulation of urea nitrogen in the blood. Their data show a slight rise in the fifth decade, but no significant change during the sixth and seventh decades, with a rather sharp increase after the 70th year. Most of the total rise from a mean of 12.9 mg urea N/100 ml blood in the 30-40 age



(From Cohn and Shock 1949)

group to a mean of 21.2 mg per cent in the 85-89 year olds occurred after the age of 70. It therefore appears that there

trend was not statistically significant. The other major electrolytes, sodium and chloride, do not show any age trend (de Billis, 1954; Herbeuval, Cuny and Manciaux, 1954; Lippi and Malerba, 1955). In our own laboratory we have found no

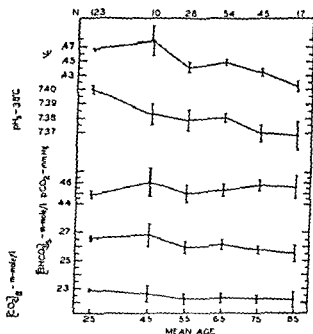


FIG. 12 Trends in the acid base equilibrium of the blood of males with increasing age. Average curves from top to bottom include percentage of red cells, serum pH at 39°, carbon dioxide tension expressed in millimetres of mercury, serum bicarbonate and blood carbon dioxide content, both expressed in millimoles per litre. The vertical lines indicate \pm one standard error of the mean. Data for the 25 year determinations taken from Hamilton and Shock (1936).

(From Shock and Yiengst, 1950)

systematic age changes in the total osmotic pressure of the plasma or its water content. The bicarbonate content of the plasma and the pH do not show significant age trends (Shock and Yiengst, 1950). Thus, under basal conditions the kidney is able to regulate the acid-base equilibrium of the body adequately, even to advanced ages (Fig. 12). Lewis and

ammonium chloride produces displacements of the acid base equilibrium in both old and young subjects. However, young individuals are able to readjust equilibrium within a period of eight hours, following a single dose of 10 g. of ammonium chloride, whereas the older subjects require as much as 24-36 hours for the process (Shock and Yiengst, 1948). When repeated daily doses of 1.5 m equiv. ammonium chloride/kg. body weight/day were administered to normal subjects for 4-7 days, the following changes were observed:

wt

(6)

load of ammonium chloride (Hilton, Goodbody and Kruesi, 1955). It was also found that the degree of metabolic acidosis induced by a standard dose of ammonium chloride showed a greater severity in the older subjects than in the young. We have now initiated a study of age differences in the ability of the individual to regulate plasma and extracellular fluid

circulation in discrete renal functions with age, the kidney retains sufficient capacity to regulate both concentrations and volumes fairly closely under conditions of rest. However, when experimental displacements are produced, age differences in the speed of readjustment appear.

There are obviously many other questions, such as age differences in glomerular permeability and the activity of specific cellular enzymes in the kidney, which remain unanswered.

Comparison in the total oxygen uptake for kidney tissue between the ages of 12 and 24 months in the rat, these differences disappear when an appropriate correction for cell number is introduced. There are, however, some specific enzymes such as

which

tion

It is

these observations to include the

after 12 hours of water deprivation falls from an average of 1.032 at age 20 to 1.024 at age 80-90. Although the absolute magnitude of the decrement is small, it is statistically significant (Lewis and Alving, 1938) and indicates impairment of the concentrating ability of the kidney, which is no doubt a reflection of the reduction in Tm as reported from our studies.

With regard to volume regulation, our observations on a

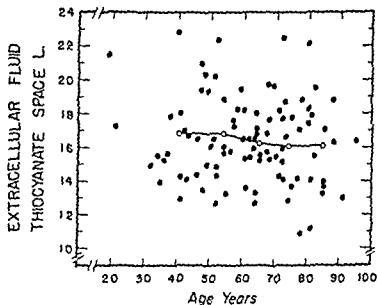


FIG. 14 Relationship between extracellular fluid space (thiocyanate space) and age in males
(From Shock, 1956)

series of 152 males failed to demonstrate any systematic changes in either plasma volume (Cohn and Shock, 1949) or in total extracellular fluid volume (Shock, Watkin and Yiengst, 1951) as estimated by thiocyanate determinations (Figs 13 and 14).

Although the aged kidney has a capacity for maintaining acid base equilibrium of the plasma under resting conditions, when an extra load is imposed upon it age differences appear. Thus, for example, we have found that a single dose of

eight hours, following a single dose of 10 g of ammonium chloride, whereas the older subjects require as much as 24-36 hours for the process (Shock and Yiengst, 1948). When repeated daily doses of 1.5 m equiv. ammonium chloride/kg body weight/day were administered to normal subjects for 4-14 days, readjustment of the acid base equilibrium occurred within 5-7 days in the young subjects, but the aged subjects (65-73 years) were unable to attain equilibrium under this load of ammonium chloride (Hilton, Goodbody and Kruesi, 1955). It was also found that the degree of metabolic acidosis

the individual to regulate plasma and extracellular fluid volume following the imposition of an oncotic load.

Thus, the evidence now available indicates that in spite of the reduction in discrete renal functions with age, the kidney retains sufficient capacity to regulate both concentrations and volumes fairly closely under conditions of rest. However, when experimental displacements are produced, age differences in the speed of readjustment appear.

There are obviously many other questions, such as age differences in glomerular permeability and the activity of specific cellular enzymes in the kidney, which remain unanswered. Studies on cellular enzymes are now in progress in our laboratory, using the rat as an experimental animal. Although we have found a reduction in the total oxygen uptake for kidney tissue between the ages of 12 and 24 months in the rat, these differences disappear when an appropriate correction for cell number is introduced. There are, however, some specific enzymes, such as succinoxidase, which show an age reduction which is apparently not dependent on the number of functioning cells in the kidney preparation (Barrows *et al.*, 1957). It is our aim to extend these observations to include the

capacity for concentrating specific substances, such as PAH, in tissue slices removed from the kidneys of animals of different ages. It is thus apparent that a great deal of research remains to be done before we can interpret age changes in renal physiology.

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DISCUSSION

Zweymüller. One of the interesting things in your paper, Dr. Shock, is the fact that the rate of excretion of PAH is not constant, but varies with the age of the animal. This is a very important point, and it is one that has not been fully appreciated by other workers in this field.

tubules and not to the glomerulus. Under normal physiological conditions we have a T_{PAH} which means that under normal

conditions this function has an important role to play in the regulation of the body water balance.

tubules that are still present in the old kidney (N.I., 77, 686). In other words the ability to determine, are just as good as those of the young. It is interesting to me because I am concerned with changes. The tubule just cannot last forever, but unfortunately the

Heller

body water you wipe out in renal function re water

Hingerty When you exclude obese patients?

Shock We did not use any index of body weight to exclude patients.

I would say immediately that in our population we do not see obese people over the age of 65. These patients were all males so we do not know anything about the weight of females.

Hingerty It seems to me that the decline in kidney function sets in at about the 50-year mark, and that is about the age when you would expect a higher incidence of obesity in the general population.

Shock Actually the body surface area decreases with increasing age in all groups of subjects we have studied. The major factor that contributes to this reduction in surface area is the body height, which goes down more than body weight. There is a wide scatter in height in our population, but there is a statistically significant linear decrement between the ages of 30 and 90. There is no significant correlation between age in the population of males and body surface area.

Shock Is there any correlation between body surface area and kidney function studies had no elevation in body surface area. This was one of the selection criteria. Every

individual in the renal function test is related to a specific gravity. Alving (1938, *Amer J Med*) found that the levels in 100 subjects aged 20 to 80. They found little increment in blood urea up to the age of about 70, but from 70 on it does increase in their data.

that the blood urea did not rise markedly in patients with low protein intake unless the glomerular filtration rate decreased to less than 25-30 ml./min.; in your work the glomerular filtration rate was far above this figure.

point to a diversion of blood from the kidneys due to this insufficient

the cardiac output results that I showed you in the average curve were not determined on the same subjects as the renal functions. We are now measuring cardiac output and renal function in the same subjects simul-

experiments at almost the same time. He did not
elevated blood pressure
identical with the
elevated blood pressure

Scribner: The question posed by these data is: is the change in the
kidney function, as described, a result of disease in the kidney
wearing out with age, or is it simply a
of the living organism?

Heller and
exchangeable potassium

Shock: We have done a good many creatinine determinations in
balance studies under conditions of a closely regulated diet. However,
I have never been able to convince myself that creatinine excretion gives
a stable value that is characteristic of the individual, because we have
seen some rather wide fluctuations that we have not been able to explain
satisfactorily. I tried it first with adolescent children and then gave it
up as I did not feel it could be determined as a characteristic
for the individual. But I am wrong.
exchangeable potassium

Bull: The lines you show with age are practically
in burns. By Probit analysis which will produce death
you chose your ordinate on the right scale, but the lines are almost
the same in that they take off at just the same age and go down in the
same way. Burning is a severe stress. We have been talking about the
elderly having a reduced tolerance to stress and burning is largely a
stress affecting water and electrolytes. The burn is a convenient
measurable lesion, and death occurs with a progressively smaller size
of burn with advancing years, which I think probably represents an
important aspect of the ageing of a regulation of water and salt.

individual in the renal series was able to concentrate his urine at least 10 times as much as the normal value, and it is not surprising that in some cases the concentration was as high as 1200 mOsm/l. in their data.

that the blood urea did not rise markedly in patients with low protein intake unless the glomerular filtration rate decreased to less than 25-30 ml./min.; in your work the glomerular filtration rate was far above this figure.

In congestive failure or other situations where cardiac output is inadequate, there is usually a decrease in renal blood flow, and an increase in tubular reabsorption of water. The normal concentration test might point to a diversion of blood from the kidneys due to this insufficient cardiac output.

It seems to me that the blood urea concentration is a poor index of renal function in these circumstances.

blood urea in a patient with congestive failure showed that in some cases the urea clearance was less than the clinical experience would suggest.

Horsli: Dr. Shock, you can see that the renal kidneys are sure greater than the clinical experience (Olbrich et al) renal functional

Renal growth and regeneration

Both the tentative and the definitive foetal kidneys develop from mesoderm, in intimate relation with the gonads. So it is not altogether surprising that the adult kidney resembles the other transient tissues and its life cycle is not completely synchronous with that of the rest of the body (Kennedy, 1957). It would be disastrous to a species, of course, if kidney and body got too far out of step, but any tendency for this to happen during reproductive life would be prevented by natural selection. There is some evidence, however, that the kidney atrophies after the climacteric, and in some species such as the rat this may limit life.

Most mammals develop their full complement of nephrons soon after birth and postnatal growth of the kidney consists chiefly of lengthening of its tubules, at first by the growth of new cells and later by hypertrophy of existing ones. When a rat is about six months old or a man about 30 years, the number of glomeruli in their kidneys begins to decrease, and it may fall to half the young adult value, without pathological change, by eighteen months old in the rat or seventy years in the man (Arataki, 1926, Moore, 1931, Roessle and Roulet, 1932). Moore and Hellman (1930) showed that removing one kidney from a rat did not slow down the loss of nephrons from the other so that involution of the kidney is an even more relentless process than that of the ovary, where removal of one gland does delay the loss of oocytes from the other (Mandl and Zuckerman, 1951).

Nowadays chemical analysis can be used to supplement histology in determining the number and size of the cells in a tissue. This is because one of the two forms of nucleic acids in cells, deoxyribonucleic acid or DNA, is confined to the nuclei, as the name suggests it ought to be, while the other, ribonucleic acid or RNA, is distributed with the bulk of the ordinary protein throughout the cytoplasm. So if DNA, RNA and protein are determined at different stages during the growth of a tissue, it is possible to distinguish between

AGE AND RENAL DISEASE

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Introduction

SENESCENCE has sometimes been described as a deterioration in homeostasis. Dr Shock showed us that the deterioration may be due to failing renal function, and this reopens an old question of whether the kidney cells themselves are less able to do their work in old people, or whether diseases of the kidney become more frequent with advancing age. It seems generally agreed that pathological lesions, particularly of the renal vessels, are very commonly found *post mortem* in old people in whom they were unsuspected during life. Oliver (1942) reviewed the controversy as to whether these lesions originate from a primary atrophy of the kidney, or are merely one of the results of generalized arteriosclerosis. He decided in favour of arteriosclerosis. The other view, that the kidney dies piecemeal, will be re-examined here because it seems possible to show that the death of some nephrons leads to pathological changes in the survivors, and some indirect ways in which this may happen will be suggested.

One can raise objections to any theory of ageing. The major defect of the definition in terms of homeostasis, it seems to the present author, is that the newborn animal finds it just as difficult to maintain a stable internal environment under stress as does the senile one. An older definition by Minot (1908), in more structural terms, described senescence as the gradual loss by differentiated cells, throughout life, of the ability to grow and to regenerate. This idea applies especially well to the kidney, as we shall see.

kidneys of the six month old rats. It may be emphasized that these findings accord very well with Minot's definition of ageing. As will be shown later, hyperplasia can and does occur in the tubules of older rats, but it does not then represent the normal primary response to loss of moderate amounts of renal tissue, and some additional stimulus, possibly endocrine in nature, is probably involved.

Renal Senescence

The compensatory changes that we have been considering are self limiting, and once they have been achieved, the kidney undergoes no further changes for many months. A different sort of tubular change will now be considered. In rats killed after 18 months of age, in occasional tubules, principally the proximal regular, orderly growth of cells in young rats' kidneys. At this age a lot of nephrons have already disappeared, but one would expect the surviving tubules to compensate for their loss by hypertrophy rather than hyperplasia. Further, this hyperplasia in ageing kidneys appears to be destructive rather than helpful, because the tubules are often blocked and functionless and eventually become dilated by hyaline casts. As age increases still further the kidneys become greatly enlarged and granular in appearance, and microscopically they show chronic interstitial fibrosis, generalized tubular dilatation, and hyaline or fibrotic changes in the glomeruli and smaller vessels. These histological changes have been described and illustrated more fully elsewhere (Kennedy, 1931, 1937). The terminal appearance has been studied by numerous pathologists, but since no two agree on a name (1912) have all been used

an increase in nuclei, or hyperplasia, and an increase of cytoplasm, or hypertrophy. This method has shown that the principal increase in the number of nuclei in the kidney of the rat occurs during the first three months of life, *pari passu* with the main growth of the skeleton, and this agrees well with histological findings.

There is a conflict of evidence about regeneration, however. Rollason (1949) showed histologically that mitosis began in the surviving kidney within forty-eight hours of unilateral nephrectomy, whereas Mandel, Mandel and Jacob (1950)

Table I

THE EFFECT OF UNILATERAL NEPHRECTOMY ON THE COMPOSITION OF THE SURVIVING KIDNEY IN RATS AT DIFFERENT AGES

| Age at Operation | Interval before Killing | Group | Total nitrogen (mg per kidney) | RNA phosphorus (mg. per kidney) | DNA phosphorus (mg per kidney) |
|------------------|-------------------------|------------------------|--------------------------------|---------------------------------|--------------------------------|
| One Month | Two Weeks | Control (not operated) | 11.3 | 0.273 | 0.165 |
| | | Kidney removed | 18.0 | 0.424 | 0.233 |
| Three Months | Six Weeks | Control | 19.4 | 0.378 | 0.181 |
| | | Kidney removed | 29.4 | 0.489 | 0.227 |
| Six Months | Six Weeks | Control | 28.1 | 0.587 | 0.253 |
| | | Kidney removed | 41.0 | 0.717 | 0.244 |

were unable to show any increase in kidney DNA even three weeks after the same operation. The difference apparently depends on the age of the animals. Table I illustrates a comparison made by the present author of the effect of unilateral nephrectomy on the composition of the surviving kidney in one-month, three-month and six-month old rats. In the youngest group, which were about the same age as Rollason used, there was a rapid increase in DNA phosphorus. In the middle group the DNA increased less than the RNA and the nitrogen, and more slowly, as Mandel, Mandel and Jacob had found. No hyperplasia at all occurred in the

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|------------------|-------------------------|------------------------|--------------------------------|--------------------------------|--------------------------------|
| One Month | Two Weeks | Control (not operated) | 11.3 | 0.273 | 0.163 |
| | | Kidney removed | 18.0 | 0.124 | 0.273 |
| Three Months | Six Weeks | Control | 10.4 | 0.378 | 0.183 |
| | | Kidney removed | 29.4 | 0.188 | 0.227 |
| Six Months | Six Weeks | Control | 28.1 | 0.597 | 0.253 |
| | | Kidney removed | 41.0 | 0.717 | 0.244 |

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adiposity and abnormal fat metabolism. If the normally fed rats with one kidney were to develop the same pathological renal changes as the overfed rats with two, then it would be reasonable to attribute the lesions to some effect associated

Table II

COMPOSITION OF THE KIDNEYS OF OBESSE RATS OR OF RATS WITH ONE KIDNEY REMOVED AT THREE AND SIX WEEKS AFTER OPERATION

| Time from operation | Group | Total nitrogen (mg per kidney) | R\A phosphorus (mg per kidney) | D\A phosphorus (mg per kidney) |
|---------------------|---------------------------|--------------------------------|--------------------------------|--------------------------------|
| | Control (not operated on) | 19.4 | 0.378 | 0.183 |
| Three weeks | Kidney removed | 27.8 | 0.504 | 0.210 |
| | Obese | 29.9 | 0.483 | 0.227 |
| Six weeks | Kidney removed | 29.4 | 0.516 | 0.289 |
| | Obese | 28.3 | 0.532 | 0.303 |

with overloading. They did develop the lesions at the same time as the obese rats at an average age of 15 months. Table III illustrates the changes in composition of the kidneys 12 months after carrying out each type of operation on three

Table III

COMPOSITION OF THE KIDNEYS OF OBESSE ANIMALS OR OF ANIMALS WITH ONE KIDNEY REMOVED TWELVE MONTHS AFTER OPERATION (OPERATED AT THREE MONTHS OF AGE)

| Group | Total nitrogen (mg per kidney) | R\A phosphorus (mg per kidney) | D\A phosphorus (mg per kidney) |
|---------------------------|--------------------------------|--------------------------------|--------------------------------|
| Control (not operated on) | 34.9 | 0.749 | 0.239 |
| Kidney removed | 73.5 | 1.479 | 0.630 |
| Obese | 70.9 | 1.972 | 0.780 |

month old animals. Note that in each case the final renal breakdown was — , the period

The pathological renal changes in old rats are almost invariably accompanied by great enlargement of the adrenals frequently by parathyroid hyperplasia, and in the later stages, at least, by cardiac hypertrophy and hypertension. Before considering further which is cause and which is effect, a description will be given of a number of ways in which similar renal lesions can be produced in much younger rats in association with the same endocrine and vascular changes.

"Senile" changes after renal overloading in younger rats

The first condition in which these lesions were found in fairly young rats was in experimental hypothalamic obesity. When the ventromedial part of the hypothalamus is destroyed electrolytically, the appetite of a rat may be doubled for several weeks and the animal becomes grotesquely fat. In view of the association of clinical obesity with renal disease and hypertension it is interesting that most of these fat rats developed typical senile kidney lesions about nine months earlier than unoperated controls (Kennedy 1951). If the animals were operated on at three months old they survived nine to 12 months before pathological lesions appeared in the kidneys but the kidneys became enlarged during the period of overfeeding soon after the hypothalamic puncture. Moise and Smith (1927) and Addis and Oliver (Oliver 1915) showed that the renal enlargement produced by a high protein diet in rats could eventually cause pathological changes and it seemed possible that this might be the way in which the kidneys were damaged in hypothalamic overfeeding. As a first step an examination was made of the chemical changes in the kidneys during the earlier stages of development of the obesity, while the food intake was very high. In Table II these are compared with the changes found previously in the surviving kidneys after unilateral nephrectomy and they followed an almost identical pattern. This suggested a convenient way to isolate the effect of simple kidney overloading during overfeeding from any possible effect of the subsequent

among the measures that Selye uses, as he says, to "sensitize" the rat to the damaging effect of hormones. Nevertheless, we have found that no overgrowth of the kidney occurs in hypophysectomized rats with hypothalamic lesions, although they still have increased appetites and other tissues, such as the liver and gastrointestinal tract, hypertrophy (Kennedy and Parrott, 1958). We also confirmed, as White, Heinbecker and Rolff (1941) first showed, that compensatory growth after partial nephrectomy required the presence of the pituitary. However, the late renal changes in our rats were associated with a catabolic rather than an anabolic state of the body as a whole, so it seems unlikely that growth hormone was being secreted in excess.

There remains the possibility that adrenal overactivity plays a part in the final renal breakdown. Adrenal enlargement and the nephrotic character of the renal defect (Saxton and Kimball, 1941) have been mentioned. A number of workers have shown that complete or extensive partial nephrectomy is followed by increased urea production (Bondy and Engel, 1947; Persike and Addis, 1949; Persike, 1950; McCance and Morrison, 1956). This has recently been shown to be due to increased protein catabolism in the liver (Sellers, Katz and Marmorston, 1957), so it may well be a result of increased adrenal activity. Overdosage with adrenal steroids can certainly cause renal breakdown associated with

associated with such experiments. We have learned little from the serum electrolytes of our rats because any changes that might implicate the adrenal are obscured by the general electrolyte retention of incipient uraemia. Morrison and Gordon (1957) however, have shown that increased urea excretion during starvation occurs both in partially nephrectomized and senile rats before obvious renal damage and is accompanied by an increased potassium loss.

Another renoprotective effect that may hasten the end of the kidney is hypertension, although again the exact relation

animal at operation, and in fact the age at which the final breakdown occurred was almost constant. To take the extreme case, rats over a year old frequently failed to establish any new renal equilibrium after either type of overloading, but rapidly developed pathological lesions.

The age at which renal failure occurred was advanced still further by increasing the renal loading, either by a more extensive partial nephrectomy, or by combining unilateral nephrectomy with overfeeding. It is sometimes said that different species tolerate the removal of different proportions of their renal tissue. It is difficult to see how a valid comparison can be made when the critical amount of kidney depends so much on the age of the animal. We found that weanling rats recovered and survived for many months after losing five sixths of their kidneys, while nine month old adults often developed acute tubular necrosis after the same operation. A probable explanation for the latent period in the younger animals is that it represents the time for the further loss of nephrons due to ageing to reduce the available kidney below the critical level. It remains to consider the part played by the associated metabolic and endocrine disturbance in destroying the kidney.

Endocrine stimuli to renal hyperplasia

A number of hormones are renotrophic. They include growth hormone (White, Heinbecker and Rolff, 1949), thyroid hormone (Korenchevsky and Hall, 1944) and testosterone (Korenchevsky and Ross, 1940). The results of treatment with growth hormone are particularly suggestive. Acute overdosage can lead to rapid kidney destruction, but treatment of a young rat for only a few days apparently causing no damage at the time, can lead to the appearance of pathological lesions months later (Selye, 1951). From the limited descriptions and photographs available no difference can be seen between these and the spontaneous lesions of older rats or those which develop after partial nephrectomy. Interpretation is complicated because partial nephrectomy is

among the measures that Selye uses, as he says, to "sensitize" the rat to the damaging effect of hormones. Nevertheless, we have found that no overgrowth of the kidney occurs in hypophysectomized rats with hypothalamic lesions, although they still have increased appetites, and other tissues, such as the liver and gastrointestinal tract, hypertrophy (Kennedy and Parrott, 1958). We also confirmed, as White, Hembecker and Rolff (1941) first showed, that compensatory growth after partial nephrectomy required the presence of the pituitary. However, the late renal changes in our rats were associated with a catabolic rather than an anabolic state of the body as a whole, so it seems unlikely that growth hormone was being secreted in excess.

There remains the possibility that adrenal overactivity plays a part in the final renal breakdown. Adrenal enlargement and the nephrotic character of the renal defect (Saxton and Kimball, 1941) have been mentioned. A number of workers have shown that complete or extensive partial nephrectomy is followed by increased urea production (Bondy and Engel, 1947, Persike and Addis, 1949, Persike, 1950, McCance and Morrison, 1956). This has recently been shown to be due to increased protein catabolism in the liver (Sellers, Katz and Marmorston, 1957), so it may well be a result of increased adrenal activity. Overdosage with adrenal steroids can certainly cause renal breakdown associated with

associated with such experiments. We have learned little from the serum electrolytes of our rats because any changes that might implicate the adrenal are obscured by the general electrolyte retention of incipient uraemia. Morrison and Gordon (1957) however, have shown that increased urea excretion during starvation occurs both in partially nephrectomized and senile rats before obvious renal damage and is accompanied by an increased potassium loss.

Another renoprival effect that may hasten the end of the kidney is hypertension, although again the exact relation

animal at operation, and in fact the age at which the final breakdown occurred was almost constant. To take the extreme case, rats over a year old frequently failed to establish any new renal equilibrium after either type of overloading, but rapidly developed pathological lesions.

The age at which renal failure occurred was advanced still further by increasing the renal loading, either by a more extensive partial nephrectomy, or by combining unilateral nephrectomy with overfeeding. It is sometimes said that different species tolerate the removal of different proportions of their renal tissue. It is difficult to see how a valid comparison can be made when the critical amount of kidney depends so much on the age of the animal. We found that weanling rats recovered and survived for many months after losing *five-sixths of their kidneys*, while *nine month old adults* often developed acute tubular necrosis after the same operation. A probable explanation for the latent period in the younger animals is that it represents the time for the further loss of nephrons due to ageing to reduce the available kidney below the critical level. It remains to consider the part played by the associated metabolic and endocrine disturbance in destroying the kidney.

Endocrine stimuli to renal hyperplasia

A number of hormones are renotrophic. They include growth hormone (White, Heinbecker and Rolff, 1949), thyroid hormone (Korenchevsky and Hall, 1944) and testosterone (Korenchevsky and Ross 1940). The results of treatment with growth hormone are particularly suggestive. Acute overdosage can lead to rapid kidney destruction, but treatment of a young rat for only a few days, apparently causing no damage at the time, can lead to the appearance of pathological lesions months later (Selye, 1951). From the limited descriptions and photographs available no difference can be seen between these and the spontaneous lesions of older rats or those which develop after partial nephrectomy. Interpretation is complicated because partial nephrectomy is

suggested that the loss of renal tissue in excess of a critical amount leads to additional renotropic stimuli, probably related to overactivity of the adrenal cortex and to hypertension, which hasten the end of the remaining nephrons.

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between cause and effect is uncertain. Wilson and Byrom (1939, 1941) showed that the production of hypertension by "clipping" one kidney could lead after a prolonged latent period to pathological lesions in the other kidney. They attributed these lesions to hypertension, because their development seemed to be arrested and the hypertension cured by removing the ischaemic kidney. Goldblatt (1947) pointed out that all the lesions Wilson and Byrom had described could occur spontaneously in rats without hypertension. More recent work, reviewed by Floyer (1957), suggests that removal of the clip, so restoring some of the lost excretory function, is a much better protective measure than removing the ischaemic kidney, which frequently increases the hypertension. The importance of extra-renal or renoprival factors in producing permanent hypertension now seems well established and certainly fits with our experience, and apparently with Goldblatt's, that hypertension and vascular changes are a late feature of the spontaneous renal disease of rats.

Much remains to be done, but it is hoped that some progress has been made towards establishing the thesis, stated at the beginning of this paper, that the essential vicious cycle of renal disease in old age, in one species at least, is the destruction of surviving nephrons by overloading after the normal renal atrophy of old age has reached a critical stage.

Summary

The kidney of the rat and of most mammals including man, begins to atrophy while the animal is still young. Pathological changes in the kidney become more frequent during involution. Irregular and apparently purposeless hyperplasia of tubular cells is a prominent feature of such lesions. Hyperplasia occurs in the tubules of growing rats both as part of normal development and as a response to a moderate increase in the excretory load, but it is not normally seen after the main growth of the skeleton is completed. The stimulus to normal renal growth probably arises in the pituitary gland. It is

(less than 20 g daily) I have no comparison with those who continued eating normal food. . . .
that our patients with nausea usually disappear
are also in better condition
protein intake often
a slight rise in serum
prevent a graft
is usually slow
A high diastolic blood pressure is a very bad prognostic factor
as we have no control group we cannot produce convincing evidence
that an untreated patient will not live as long as our 'maltreated' patients

Kennedy Have you done any liver function tests in a situation where serum albumin is falling in spite of a high protein intake, Prof. Borst? There may be a possible connexion with the increased liver protein breakdown when one removes the kidney (Sellers, Katz and Marmorston, (1937) *Amer J Physiol*, 191, 345)

Borst No liver function tests were done, and we only have data on the serum proteins. There is no increased γ globulin as is usually found in chronic hepato-cellular disease. We had, however, some evidence of a deleterious effect of the low protein diet. More cases of tuberculosis were seen than would be expected in similar patients on a normal protein diet and two patients died from miliary tuberculosis. Probably the extremely low protein diet reduces the resistance against the tubercle bacillus in spite of the fact that the patients do not lose weight.

Talbot How do you define a low protein diet?

Borst It is less than 20 g/day. To control the diet and determine whether or not the patient adheres to it, 24-hour urine portions are regularly examined for nitrogen excretion. We also determine creatinine excretion to be sure that urine collection is complete. The 24-hour creatinine output is very constant. This output is determined for every kidney patient during clinical observation, and we use the figures for comparison with the nitrogen output when the patients are under control in the out-patient department. Many adhere to the diet and go along very well for several years.

Felfar We have had similar experiences in Czechoslovakia. This treatment originated in the experiments of Thomas Addis (1948 *Glomerulonephritis. Diagnosis and Treatment* New York: Macmillan), who showed that partially nephrectomized rats kept on a higher protein intake could not survive as long as the animals with a low protein diet. We therefore started to use a low protein diet in all patients with chronic glomerulonephritis. Usually we give 0.5-0.7 g/kg body weight per day in the diet (but no less than 0.5 g/kg) plus the amount lost in the urine. Of course, children and those with the nephrotic syndrome are given larger amounts of protein. It is very difficult to judge long term results as we have no control group for this treatment. Nevertheless we do think we can prolong the life of patients with chronic nephritis on this low protein diet.

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DISCUSSION

Sayer You said that this renal damage in the obese rat might be a question of protein overloading. Did you try feeding these rats on an isocaloric diet but with half the protein content?

Kennedy I have tried it as a short term experiment but I did not carry it to its logical conclusion. There was no renotrophic effect.

Sayer Over feeding is itself a stressful activity in the Selyeian sense and that alone might lead to adrenal over activity. Certainly there is clinical evidence that it may. Obese people who give evidence of increased adrenal steroid production may cease to do so after they have been put on a diet and have had their weight brought down to normal.

Kennedy To answer that I must challenge the question of whether in fact stress ever produces renal lesions in the rat. I can do that quickly by quoting some recent work by Crane, Baker and Ingle (1958 *Endocrinology* 62, 216 and Crane and Ingle *Endocrinology* 62, 174) who have studied a large number of so called stresses which sound quite barbaric and have found that the only one which produces what Selye calls the stressed kidney is exposure to cold. Selye has always said that this is the most effective and these workers now say that it is the only effective stress. Under those circumstances the rats eat twice as much food. If they are then fed isocalorically as you suggest with a high caloric diet made up with carbohydrate and fat they do not develop lesions. These workers attribute renal lesions to overloading with salt. I choose protein.

Talbot Will you take this as evidence in favour of restricting the protein intake of patients with handicapped renal function?

Kennedy I can see that it would be a dangerous thing to press a trophic stimulus like a high protein intake too far in an attempt to get recovery. Are you thinking of chronic renal disease or a recovery from acute damage?

Talbot Both.

Kennedy Purely from my own findings I would have said that I could see no point in producing additional renal growth in trying to help recovery of the kidney by giving a high protein diet if the object was simply to replace protein lost from the body then my results of course are not relevant. I think the problem of a high protein intake has to be studied from this point of view on the human and we cannot answer from the work on the rat. Moreover there may be a totally different limitation to the structural renal reserve in the rat which has a kidney of completely different anatomical character.

Bord We treat all patients with a kidney function of less than 10 per cent of normal with a diet adequate in calories but very poor in protein.

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of not the patient adheres to it, 24 hour urine portions are regularly examined for nitrogen excretion. We also determine creatinine excretion to be sure that urine collection is complete. The 24-hour creatinine output is very constant. This output is determined for every kidney patient during clinical observation, and we use the figures for comparison with the nitrogen output when the patients are under control in the out patient department. Many adhere to the diet and go along very well for several years.

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Richet: In populations that are said to eat a lot of proteins, for instance Eskimos, what is the state of the kidney? Do such people often die from chronic nephritis? They are generally said to eat 5,000 cal./day, mostly fat and proteins.

a man of about 10-45.

Dr. Talbot: you mentioned the amount of protein given in cases of chronic nephritis. In Paris we put some chronic nephritic patients on an

they would never live anyway; we prefer to have a patient with perhaps a shorter life, but healthy, than the other way round.

Fourman: Dr. Kennedy, why did you imply a relationship between catabolic reactions, adrenal hyperplasia and Selye's results with cortexone acetate?

Kennedy: The catabolism would require over-secretion of Compound F, of course. However, Hechter and Pincus (1954, *Physiol. Rev.*, 34, 150)

results with cortexone acetate?

Kennedy: Yes, in that cortexone acetate was the particular steroid

potassium depletion are similar in

repeated these experiments with dietary potassium depletion and col-
 young rats and were unable
 conclusively at Cambridge.
 to permanent damage from
 h Dr. Fourman's suggestions
 lye.

Kennedy Dr. Fourman and I have looked at potassium-deficient

that

Fourman: That seems to correspond to what we have seen in

be worse in older rats

Kennedy. It is a vicious cycle and we are coming into it at different points

RENAL FUNCTION IN RESPIRATORY FAILURE

D A K BLACK

Department of Medicine Royal Infirmary, University of Manchester

WITH increasing age, the functional capacity of the lungs and of the kidneys declines. Respiration is embarrassed by increasing rigidity of the chest wall, and there is also an increase in the respiratory dead space of the lung itself in older subjects (Comroe *et al*, 1955). The kidneys lose efficiency in consequence of a progressive loss of nephrons, which may reduce the nephron population to 60 per cent of the original number, the impairment of renal function is indicated by a fall in the clearance of inulin and of *p* aminohippurate, and in the maximal reabsorptive capacity for glucose (Tm_g) (Shock, 1952). The blood pH in old people is a little lower, and their plasma returns more slowly to its previous level after imposed loads of either acid or alkali. These various encroachments on functional reserve are probably of no great moment in healthy old folk leading a normal life, but they are brought into prominence when respiratory function is pathologically impaired by the related changes of chronic bronchitis, bronchospasm, and emphysema. In an urban population, the incidence of chronic bronchitis in old people has been found to be 40 per cent (Sheldon, 1948), this common illness leads in time to gross respiratory failure, with the patient afflicted by anoxia, hypercapnia, and increased pulmonary vascular resistance in varying degrees. There are several ways in which advanced respiratory failure can increase the demands on the kidneys, and also diminish their functional capacity. This communication outlines the effects on renal function of chronic hypercapnia and of cardiac failure secondary to emphysema (*cor pulmonale*).

Hypercapnia The effects of acute hypercapnia, usually induced by inhalation of 5-10 per cent CO_2 , have been reviewed by Pitts (1953). There is a fall in plasma pH and a rise in pCO_2 , the urine formed is acid, and the reabsorption of filtered bicarbonate is virtually complete, although the amount of filtered bicarbonate has been increased by the experimental procedure. Enhancement of bicarbonate reabsorption is the most striking change in renal performance induced by acute hypercapnia and it persists when the fall in plasma pH is prevented by infusion of bicarbonate, so that in this context rise in pCO_2 seems to be the more relevant stimulus to bicarbonate reabsorption. The reabsorption of bicarbonate is also increased in subjects depleted of potassium, in whom intracellular pH is probably decreased, so it seems quite likely that the effect of raised pCO_2 on bicarbonate reabsorption is mediated by a fall in the pH of the renal tubule cells. Apart from this rather striking change in bicarbonate excretion the output of electrolytes is not significantly affected by short periods of hypercapnia, although there is a transient water diuresis (Barbour *et al*, 1953).

It is not clear how far the information obtained from studies of acute hypercapnia can be applied to the situation of chronic hypercapnia found in emphysematous patients. Here a steady state has been established at a new level of plasma pH and bicarbonate concentration. The electrolyte composition of plasma and red cells in emphysematous

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(Pitts and Greaves 1957). For

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The mean urinary pH in these two patients was 6.26 and 6.67, no more acid than specimens from two 'controls' with mean pH of 6.18 and 6.20. The mean excretions of bicarbonate were 7.5 and 15.2 m mole/day, compared with 10.1 and 4.8 m mole/day in controls. Ammonium excretion was somewhat higher, and titratable acidity somewhat lower in the patients with respiratory acidosis than in the controls, and it has been reported that renal glutaminase is increased in experimental respiratory acidosis. There were no striking differences in 24 hour output of sodium, potassium or chloride. These findings are consistent with the view that renal adaptation has included increased synthesis of ammonia allowing the excretion of hydron at a higher urine pH than in acute respiratory acidosis, without increase in urinary buffer (the excretion of phosphate was lower than in the controls).

In preliminary observations on four patients with respiratory acidosis, my colleague Dr J. Timoner has found a pH range in urine of 5.1 to 6.7, with ammonium excretion up to 65 μ equiv/min and titratable acidity up to 60 μ equiv/min. After a standard load of ammonium chloride (0.1 g/kg body weight), two patients excreted 76.5 and 81.3 μ equiv of ammonia, and 26.3 and 46.2 μ equiv of titratable acid per minute. The ammonium excretion is just above the normal range found by Davies and Wrong (1957). These two patients were aged 57 and 60, and seem to have retained the capacity of the renal tubule cells to form ammonia in response to an acid stimulus.

Renal function in cor pulmonale In the cardiac failure associated with emphysema the cardiac output is commonly increased, and the patient has warm extremities. Terminally, the limbs become cold, the blood pressure falls and the cardiac output at this stage is reduced. Davies and Kilpatrick (1951) showed that even in the high output phase of cor pulmonale the circulation through the kidneys and the glomerular filtration rate were substantially diminished. These findings have been confirmed by Lewis and his co

workers (1952) A moderate degree of urea retention, presumably on the basis of relative renal ischaemia, is common in cor pulmonale (Simpson, 1957), as in other forms of heart failure In patients dying from heart failure, the output of urine may be reduced to below 500 ml/day, but complete suppression of urine does not seem to have been recorded, even in the terminal stages It is perhaps of some interest, therefore, that over the past ten years we have seen two patients, both with cor pulmonale, who became anuric (Black and Stanbury, 1958) One of them, a girl of 20 with widespread bronchiectasis and a terminal bronchopneumonia, had an eight day period of extreme oliguria, during which her blood urea rose to 158 mg/100 ml She was treated conservatively, urine was again formed, and the blood urea fell to 76 mg/100 ml She continued to pass considerable amounts of dilute urine until her death a week after the end of the anuric period The second patient, a man of 44, passed no urine for over 24 hours, and had no urine in his bladder after death Both these patients had hypotension and cold extremities, and were presumably in the low output phase of cor pulmonale, but cardiac output could not of course be measured Both of them had central cyanosis, but only the second had a raised $p\text{CO}_2$ in the plasma The main factor in causing anuria was probably renal ischaemia, but this may have been aggravated by arterial desaturation

Both these patients had hyperkalaemia and low plasma sodium This association is fairly common in patients with acute renal failure

Partial replacement by sodium

These observations in patients with terminal cor pulmonale are possibly of little more than academic interest, but they perhaps constitute yet another argument for the early treatment of intercurrent infections in patients with acute

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DISCUSSION

Milne: I am not convinced, Dr Black, that the anuria you mentioned

dary staphylococcal pneumonia. A severe respiratory infection of itself in some cases seems to be able to precipitate anuria, and I myself prefer to relate your experience to infection rather than to the biochemical changes of chronic respiratory acidosis.

I have a tremendous respect for you to think we should avoid bicarbonate. To the chemist bicarbonate is a base itself. Bicarbonate does not

When you say infection, do you mean infection leading to a fall in

Milne. No, because I am not sure that these cases occurred in young adults without any evidence

whatsoever of chronic respiratory disease, and that a severe respiratory infection, for some reason that I do not know, may cause acute tubular necrosis, for which there is autopsy proof in one case.

Black This would really bring it into the whole group of peripheral circulatory changes

McCance This seems to me a matter which is wide open to experi-

Horst We have just had an autopsy on a very obese patient who died with bilateral cortical necrosis. I am ashamed to say that she had been under-examined. As in Dr. Black's cases she was admitted with a respiratory infection which was treated with penicillin, and in a few days the infection was under control. She was up and about until we dis-

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DISCUSSION

Milne I am not convinced Dr Black that the anuria you mentioned in your two cases is in any way related to the chronic respiratory disease. During the last influenza epidemic in this country some cases of anuria were associated with influenza. I know of one case in Dundee and we ourselves have personally studied three cases. Two of those we saw recovered and one died. The one that died showed typical acute tubular necrosis, the other two showed a clinical course typical of tubular necrosis. None of these patients gave any sign of chronic respiratory

dary staphylococcal pneumonia. A severe respiratory infection of itself in some cases seems to be able to precipitate anuria and I myself prefer to relate your experience to infection rather than to the biochemical changes of chronic respiratory acidosis.

do not fall in cardiac output and renal vasoconstriction or do you mean an infection of the kidney?

Milne No certainly not an infection of the kidney. All I am stressing is that these cases occurred in young adults without any evidence

WATER AND ELECTROLYTE METABOLISM IN CONGESTIVE FAILURE

Z FEJFAR

*Institute for Cardiovascular Research,
Prague—Krd*

The rôle of the kidney in congestive failure

THE genesis of abnormal water and electrolyte metabolism in congestive failure is at present generally attributed to impaired renal function. It was previously thought that increased systemic venous pressure (and hence the imbalance of Starling forces in the capillaries) was the main factor initiating these phenomena. Warren and Stead (1944) observed in some cardiac patients an increase in body weight after the administration of salt before any significant rise in central venous pressure. This indicated that another mechanism might be responsible for the retention of salt and water in chronic congestive failure. Merrill (1946) confirmed the earlier findings of Seymour and co-workers (1942) that patients with congestive failure have a diminished renal blood flow, moreover he found that the decrease in renal blood flow was far greater than the diminution of cardiac output.

It was however, not clear whether the retention of electrolytes and water in chronic congestive heart failure was due to a primary decrease in renal function or to the decrease in renal blood flow and function as a consequence of the increase in central venous pressure.

It appeared to us in 1947 (see Brod and Fejfar, 1949, 1950) that only observations of haemodynamic events at the time when water balance was changing could elucidate this problem. Patients with heart disease on the borderline of right heart failure usually have a low urine output during the day, but an increased urine flow at night. This spontaneous diuresis

attempt to compensate them artificially by getting their serum bicarbonate levels up. We treated a 50 year old man with acute respiratory acidosis whose initial bicarbonate figure was 10 m-equiv/l and the blood pH breathing room air about 7.28. When he went into oxygen he became unconscious rather quickly, presumably due to the decrease in ventilation from the relief of anoxia. He was removed from oxygen and over the next 18 hours dialysed through a cellophane bag in his stomach using a fluid containing 50 m-equiv/l sodium bicarbonate in 5 per cent glucose. The dialysis elevated his serum bicarbonate to 64 m-equiv/l despite a negative sodium balance of 200 m-equiv. The sodium was lost mainly in the urine. The high serum bicarbonate elevated his blood pH breathing room air to 7.55. When he again went into oxygen his blood pH fell to 7.45 and he did not become unconscious. His anoxia disappeared despite the fact that his ventilatory rate slowed from 9 litres per minute to 3 litres per minute. For 7 hours his kidneys sustained his serum bicarbonate level by excreting 100 m-equiv.

Endogenous acidosis is acute and high pCO_2 . The results also suggest that serum bicarbonate renal compensation for the respiratory acidosis may be incomplete in this acute situation. Gastrodialysis makes it possible to treat the acidosis without resorting to sodium administration which is contraindicated because of the heart failure from cor pulmonale.

decompensation, the central venous pressure being normal (Fejfar and Brod, 1949; Blegen and Aas, 1950; Werko *et al.*, 1952a; Himbert *et al.*, 1954; Werko *et al.*, 1955).

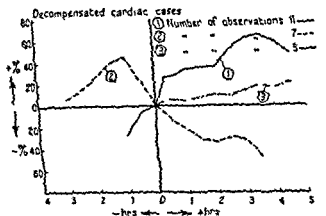


Fig 2 presents the individual values of renal blood flow in normal subjects and in patients with heart diseases. All patients are divided into five groups according to the clinical degree of heart failure

In the first group are clinically compensated patients. The second group includes patients with a slight to moderate dyspnoea on effort, in the third are those with marked dyspnoea on effort, orthopnoea or attacks of nocturnal dyspnoea and acute pulmonary oedema. The fourth group covers patients with signs of right-sided decompensation who responded well

reflects a temporary improvement of the impaired water balance. It runs its course within a few hours. It was therefore possible to follow the sequence of events and investigate the relationship between central venous pressure, systemic and renal haemodynamic changes, and renal function.

Cardiac output, right auricular pressure, water content of plasma, and renal function (renal blood flow, glomerular filtration rate and excretion of electrolytes) were studied from the early hours of the afternoon until the following morning in ten normal subjects and 25 patients with heart disease of different origin. 19 of them having congestive failure of varying degree (Brod and Fejfar 1949, 1950, Fejfar and Brod, 1950a b d).

Cardiac output was measured by a direct Fick method and right auricular pressure by a water manometer attached to the cardiac catheter. Changes of water content in plasma were assessed from the percentage change in plasma proteins, haematocrit and the disappearance curve of Evans blue. Renal plasma flow was estimated by the clearance of PAH (*p*-aminohippuric acid), glomerular filtration rate by the clearance of inulin, and chlorides by the Van Slyke and Hiller (1947) modification of Sendroy's method.

A nocturnal diuresis was observed in 11 patients with congestive failure. In none of them was it preceded by a decrease in right auricular pressure. On the other hand the increase in urine output at night started in all these patients with an elevation in renal blood flow. The decrease in urine flow at night occurred in seven decompensated cardinals. In all of them it was associated with a diminution in renal blood flow (Fig. 1). The increase in renal blood flow was not related to a similar change in cardiac output which increased simultaneously in only half of the investigated subjects.

There is thus evidence in dynamic observations that the increase in central venous pressure in congestive failure is not the primary cause of cardiac oedema, the main factor being impaired renal function.

A low renal blood flow with a diminished glomerular

filtration rate and increased tubular reabsorption of electrolytes was also found in patients with left-sided failure and with mitral stenosis without any clinical evidence of right-sided decompensation, the central venous pressure being normal (Fejfar and Brod, 1949; Blegen and Aas, 1950; Werko *et al.*, 1952a; Himbert *et al.*, 1954; Werkö *et al.*, 1955).

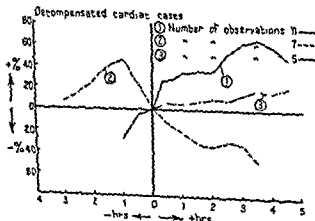


FIG. 1. Composite diagram showing percentage change in RBF over time in decompensated cardiac cases.

(Werko *et al.*, 1955)

Fig. 2 presents the individual values of renal blood flow in normal subjects and in patients with heart diseases. All patients are divided into five groups according to the clinical degree of heart failure.

In the first group are clinically compensated patients. The second group includes patients with a slight to moderate degree of heart failure. The third group covers patients with signs of right-sided decompensation who responded well

to digitalis, and in the fifth group are patients refractory to the usual methods of treatment

It may be seen that patients without right sided failure have a decreased renal blood flow in comparison with the values in normal control subjects

On the other hand increase of pressure in the renal vein brought about by a partial occlusion (Selkurt, Hall and

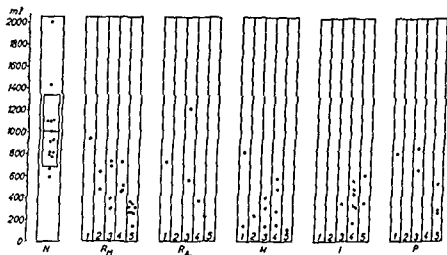


FIG. 2 Renal blood flow in normal sub (R_N and R_{Ah}) hypertensive (II) ischr disease III patients are divided into 1 degree of heart failure

Spencer, 1949), or by an increased abdominal pressure (Bradley and Bradley, 1947), is followed by only a small diminution of the renal blood flow

Maxwell, Breed and Schwartz (1950) measured pressure in the inferior vena cava in 17 healthy subjects and ten patients with congestive failure. The mean pressure in healthy subjects was 15.2 cm H_2O , and in patients with congestive failure 27 cm H_2O . From the measured values of pressure they calculated that the increase of renal resistance due to the elevation of pressure in renal veins would reduce renal blood flow by about 14 per cent. The actual decrease in renal blood flow in congestive failure is far greater (see Fig. 2)

Farber and co workers (1951, 1953) studied in man the effect of an increase of pressure in the vena cava produced by means of a balloon above and below the orifice of the renal veins. In both procedures there was a diminution of renal blood flow, glomerular filtration rate and excretion of water and electrolytes.

The increased central venous pressure in congestive failure may, of course, contribute to reduction in renal function (Briggs *et al*, 1948, Bradley and Blake, 1949, Earle *et al*, 1949). It determines the distribution of retained water and electrolytes which in left sided failure is in the lungs and in congestive failure mainly in the lower part of the body.

The nature of renal changes in congestive failure

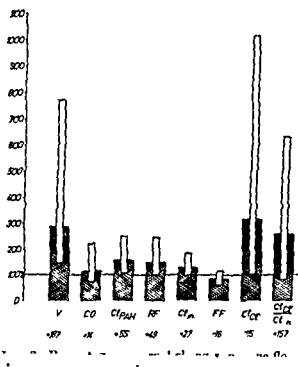
The nocturnal increase of diuresis and renal blood flow in our investigated patients with congestive failure was also associated with an elevation of glomerular filtration rate and with a decrease in tubular reabsorption of water and electrolytes. This may be seen in Fig 3, which covers 20 spontaneous changes in urine flow in 14 patients with congestive failure. The lower urine output was always taken as the initial value (100 per cent).

The mean increase in renal blood flow was 55.5 per cent (from 6 to 146 per cent). Only three times was the increase in renal blood flow smaller than 20 per cent. In 14 subjects in whom it was measured cardiac output (CO) rose significantly in six instances, fell in three and did not change in five. It is clear that the increase in renal blood flow could not depend on the primary increase in CO. This is confirmed by an increase in the renal fraction of cardiac output in all instances except one, in which it was 15 times.

Glomerular filtration rate (GFR) was 27.4 per cent, with the range - 4.5 to + 82 per cent.

The elevation of renal blood flow was effected in the great majority by a decrease in postglomerular resistance, the filtration fraction diminishing 17 times and increasing in only three instances

The increase in chloride clearance was of the same order as



clearance to glomerular filtration rate ($\frac{Cl_{cr}}{Cl_{cr}}$) The mean percentage change (\blacksquare) and range (\hatchedbox) in 14 patients with heart failure are presented. The lower urine output was taken as 100%.

the elevation of urine volume. The mean increase was 215 per cent, range 2 to 910 per cent. The ratio of chloride clearance to glomerular filtration rate rose on an average by 157 per cent (range -17.6 to +530 per cent).

According to Wesson, Anslow and Smith (1948) some 85 per cent of the filtered sodium and chloride is reabsorbed by an active mechanism in the proximal tubule, irrespective of the amount filtered. The reabsorption of the remaining 15 per cent of sodium and chloride is limited by a fixed maximal rate at which the distal tubular cells are able to reabsorb these electrolytes. Whenever the tubular chloride load decreases with a fall in glomerular filtration rate in the presence of this maximal reabsorption capacity, almost all of the filtered chloride is reabsorbed. Merrill (1949), Mokotoff, Ross and Leiter (1948), Selkurt, Hall and Spencer (1949), Stead (1951) and others are of the opinion that in congestive failure this mechanism leads to the maximum reabsorption of electrolytes and water, that is to say that the diminution of glomerular filtration is such that with a normal unchanged tubular reabsorption, water and electrolytes are retained.

Our results are not in accord with the hypothesis of Wesson, Anslow and Smith. In patients with severe congestive failure, glomerular filtration rate did not rise towards normal levels at the time of nocturnal diuresis, in spite of this, the amount of excreted chloride was far greater than the quantity of chloride excreted at night in healthy subjects with a normal glomerular filtration rate. Fig. 4 demonstrates that the tubular reabsorption of chloride can vary markedly with a constant tubular chloride load. It is clear, of course, that at a given chloride load less chloride is reabsorbed at a high than at a low urine flow.

The concentration of chloride in urine exceeded its plasma level in only seven out of 24 observations at high urine flow. The increased urine flow, therefore, cannot be explained on osmotic grounds by an increased excretion of chloride.

The lower elimination of electrolytes and water -

is stated by Briggs and co workers (1948), Kattus and co workers (1948). Davis and Shock (1949), Newman (1949),

Humbert and co workers (1954), Cort (1955b), Cort and Fencel (1957), and others

Doyle and Merrill (1957) studied renal function in 18 patients with congestive failure in a supine position and tilted in a passive erect posture. The changes were qualitatively similar to those in normal subjects. There was a further depression of renal plasma flow, glomerular filtration rate and also a decreased urine flow and a fall in the excretion of the

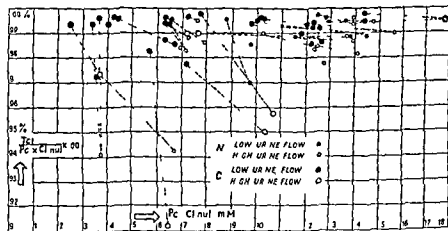


FIG 4 Relationship of the amount of the chloride filtered ($P_{Cl} \times Cl_{nul}$) and reabsorbed ($\frac{T_{Cl}}{P_{Cl} \times Cl_{nul}} \times 100$) in individual subjects at high and low urine flows. Values in individual subjects are connected with dotted lines. N—normal control subjects. C—patients with heart disease. See text for details.

electrolytes. In accord with our previous findings, with nocturia the decreased urine flow in the erect posture was closely correlated with changes in renal plasma flow. There was, on the other hand, a very poor correlation between changes in glomerular filtration rate and sodium excretion.

In these observations there was an indirect relationship between the tubular reabsorption of electrolytes and water and renal blood flow. The tubular reabsorption increased when renal blood flow fell and *vice versa*.

This finding does not characterize congestive failure alone

Bucht and co-workers (1953) studied the haemodynamic changes together with the excretion of sodium in eight healthy human subjects during muscular exercise of varying degree. As long as the effort was small (oxygen consumption not above 500 ml/min), an increase of CO was found without significant effect on renal blood flow, glomerular filtration rate or excretion of sodium. A greater muscular effort (oxygen consumption about 1,000 ml/min) was characterized by a marked increase in CO (almost double) and a simultaneous fall in renal blood flow and the renal fraction of CO. The excretion of sodium and water fell. Glomerular filtration rate and pressure in renal veins did not change significantly. Similar results were observed in patients with heart disease (Judson *et al.* 1955, Humbert, Scébat and Théard 1956). Increase of tubular reabsorption was therefore responsible for the diminished excretion of sodium and water.

The close relationship between renal blood flow and excretion of electrolytes in congestive failure is striking. We have expressed the opinion (Brod and Fejfar, 1950) that decreased renal blood flow directly impairs the excretion of water and electrolytes. A smaller glomerular filtration rate diminishes tubular electrolyte load and, owing to a slower flow of tubular urine a greater proportion of the filtered amount is reabsorbed. We could not, of course, exclude another possibility that increased reabsorption of water and electrolytes in the renal tubules could occur parallel with, but independently of the diminished renal plasma flow, i.e. the stimulus for the renal vasoconstriction could directly influence the function of renal tubules, leading to an increased reabsorption of salt and water.

Humoral and neural regulatory mechanisms in congestive failure

Some known humoral and neural factors can alter the function of renal tubules. In the urine of patients with congestive failure renin (Merrill, Morrison and Brannon, 1946), VM (vaso excitor material) and VDM (vasodepressor

material) have been found (Edelman *et al*, 1950). Extracts of urine from patients with congestive failure contain anti diuretic material (Bercu, Rokaw and Massie, 1949, 1950) with a great sodium retaining activity (Deming and Luetscher, 1950*a,b*), which disappears when the patients become compensated (Luetscher, Deming and Johnson, 1950, 1951). The substance responsible for this is aldosterone (Luetscher and Johnson, 1954). An increased excretion of aldosterone is not characteristic only of congestive failure, but accompanies nephrotic and cirrhotic oedema as well. A permanent increase of aldosterone under these conditions is called secondary aldosteronism (Conn, 1955; Bartter, 1956; Milne and Muehrcke, 1956; Thorn *et al*, 1956; Liddle, Duncan and Bartter, 1956; Wolff, Koczorek and Buchborn 1957).

The increased secretion of aldosterone in congestive failure may be important in some patients, as can be seen from the favourable effect of bilateral adrenalectomy (Thorn *et al*, 1956).

Buchborn (1956) estimated the activity of plasma anti diuretic hormone (ADH) by a sensitive biological method on the toad, together with serum osmolarity. He found a close indirect correlation between the plasma ADH and serum osmolarity in 14 normal subjects, in patients with hepatic cirrhosis, in compensated cardiac patients, and also in patients with congestive failure. The increased plasma level of ADH in congestive failure is not therefore primary, being an expression of the homeostatic function of ADH, regulating osmotic pressure in the organism (Buchborn, 1956).

Neither ADH nor aldosterone significantly influences circulation in the kidneys. Their main effect is on renal tubules where they increase the reabsorption of water (ADH) or sodium (aldosterone). In addition we have already indicated that the vasoconstriction in the kidneys, together with diminished elimination of sodium, occurs during a short muscular effort (10 minutes, Bucht *et al*, 1953). The effect of aldosterone would be slower. According to Bartter (1956) the excretion of sodium in a patient with Addison's disease did

not start to fall until more than an hour after intravenous injection of 40 μ g aldosterone

It would appear to us, therefore, that neither of these humoral substances is the primary cause of the retention of salt and water in heart failure

The results of haemodynamic changes in human subjects following intravenous injection of Dibenamine called our attention to the importance of reflex (neurohumoral) regulation in the genesis of haemodynamic changes in congestive failure

Blockade of adrenergic impulses by Dibenamine in patients with heart failure caused a diminution of a high peripheral vascular resistance and central venous pressure. Cardiac output increased. Renal blood flow rose in a great majority of investigated subjects, suggesting that this was independent of the increase in CO. These changes were not produced by blocking the adrenergic impulses in the heart or by an increased secretion of adrenaline (Fejfar and Brod, 1950c, 1951, 1954, Brod Fejfar and Fejfarová 1951, 1954) (Fig 5). The increase in renal blood flow in seven out of nine patients in congestive failure was accompanied by a rise in urine flow and an increased elimination of sodium or chloride.

We were able to conclude from our results that, with the onset of congestive failure, reflex (neurohumoral) vasoconstriction develops in both arterial and venous circulation. The function of this selective vasoconstriction may be to secure a sufficient supply of oxygenated blood to working tissues such as the heart and other muscles.

A haemodynamic pattern resembling chronic heart failure (i.e. unequal distribution of blood supply to various organs, increased utilization of oxygen in tissues, and an insufficient CO) may also be found in clinical circumstances with a diminished return of venous blood to the heart (e.g. mitral stenosis, constrictive pericarditis), or when the amount of circulating blood and oxygen decreases, as well as in acute heart failure or peripheral circulatory failure (see Fejfar, 1958). A similar haemodynamic picture can be seen in severe

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 " " *et al*, 1953). The effect of
 ing to Bartter (1956) the
 the Addison's disease did

A high central venous pressure and a secondary excretion of humoral substances like aldosterone complicate the response

Werkö and co-workers (1955), in a study of systemic and renal haemodynamic changes in 146 subjects with different cardiac disorders came to a similar conclusion. Their results suggest that "the adrenergic impulses could contribute to the diminished renal blood flow in severe heart disease before any signs of congestion are apparent". They think one of the factors causing the release of adrenergic impulses may be a decreased stroke volume.

The origin of the afferent impulses of this functional haemodynamic reflex is not known. There are, of course, several pieces of evidence on the influence of nervous impulses on diuresis. Viar and co-workers (1951) demonstrated an increase in urine flow and excretion of sodium as the result of a rising venous pressure in the head (following the compression of neck by a manometer cuff). Cort (1953), in agreement with these results found an increased diuresis with higher elimination of sodium in subjects with the head lowered (Trendelenburg position of 15°). The changes in renal blood flow were not reported. Cathcart and Williams (1955) did not confirm this.

Gauer and co-workers (1954) described an increase in urine flow in anaesthetized dogs during the negative pressure breathing period. This was also found in healthy human subjects (Sicker, Gauer and Henry, 1952, 1954). The rise in diuresis was not accompanied by increased elimination of electrolytes (Na^+ or K^+). This water diuresis was thought to be caused by stimulation of volume or stretch receptors localized in the cardiovascular system in the thorax (left atrium or pulmonary veins). The values of renal plasma flow were not measured in these experiments. We do not know, therefore, if the changes reported were produced by a direct influence on the renal tubules without any change in

muscular effort in healthy subjects. It differs from that found in heart failure by an increase in CO and by vaso dilatation in the skin due to increased temperature.

Haemodynamic changes in heart failure therefore do not represent a new and special adaptation of the organism to the

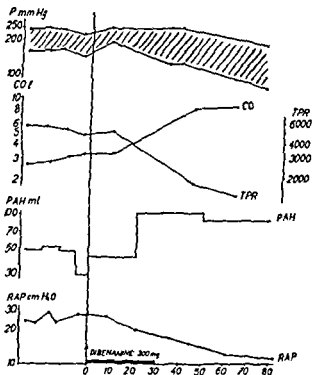


FIG 5 Changes in cardiac output (CO) peripheral vascular resistance (TPR) blood pressure (P) right auricular pressure (RAP) and renal plasma flow (PAH) after Dibenamine in a subject with heart failure. See text for details (Fejfar / (1957) *Acta cardiol (Brux)* 12, 13)

diminishing performance of the heart. They are a typical reaction which appears in every situation in which CO is inadequate for oxygen requirement in the tissues. This reaction becomes a chronic feature during the development of congestive failure and leads to retention of water and sodium

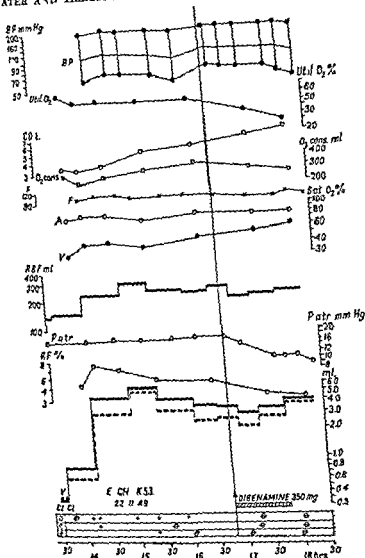


FIG. 6. Haemodynamic changes and renal excretion of chloride in a patient with acute pulmonary oedema. BP—blood pressure, F—pulse frequency, Ut/O₂—oxygen utilization in tissues (in percentage of O₂ supply), O₂ cons.—oxygen consumption/min, CO—cardiac output, Sat. O₂—arterial (A) and mixed venous (V) oxygen saturation as a percentage, RBF—renal blood flow, RBF—renal fraction of cardiac output; V—urine flow in ml/min, Cl—chloride clearance, Patr—right auricular pressure, D—dyspnoea, C—cough, R—râles.

evidence (see above) that renal blood flow and a decreased excretion of electrolytes occurs in left ventricular failure and mitral stenosis without right sided decompensation, when there is an increased pressure in the venous side of the pulmonary circulation

On occasion, however, a sudden increase of pressure in this part of the pulmonary circulation may be associated with a rise of urine flow in patients with a heart disease. We have followed haemodynamic changes in nine patients with acute pulmonary oedema (Tejfar *et al.*, 1958a), in three of them we also studied renal haemodynamics and the excretion of electrolytes. At the onset of recovery from pulmonary oedema there was a depressed renal blood flow and the renal fraction of CO started to increase before any significant changes in cardiac output occurred. In two of these three patients the rise in renal blood flow was accompanied by an increased excretion of chloride (Fig. 6). A rise of pressure in the left auricle and pulmonary veins is typical for acute pulmonary oedema in patients with mitral stenosis or left ventricular failure. It is therefore possible that this elevation of pressure could influence renal blood flow, diuresis, and the excretion of electrolytes. The diuresis was not, however, a water diuresis as described by Sicker, Gauer and Henry (1952, 1954).

Gömmert and co workers (1954) studied renal circulation in dogs with crossed circulation under hypoxaemia. They found a decrease in renal blood flow in a dog whose head was perfused from the other body by hypoxic (venous) blood. Following denervation of the kidneys, this vasoconstriction either disappeared completely or was insignificant.

Foldi and co workers (1955) found in hypoxaemic dogs a decrease in renal blood flow, excretion of water and electrolytes. In healthy subjects breathing a mixture of 10 per cent oxygen there was also a decreased renal blood flow and elimination of electrolytes. On the other hand a low renal blood flow, glomerular filtration rate and excretion of sodium significantly increased in patients with congestive heart

concentration of oxygen) CO rose in a similar way to the rise observed in hypoxaemic hypoxia in intact animals

(d) Harrison and co workers (1927) concluded from their studies on experimental hypoxaemia in dogs that the oxygen tension in the myocardium is the most important factor determining the rise in CO

A direct efferent nervous influence on the kidneys was demonstrated by Kaplan and Rapoport (1951) and Blake (1932) in dogs with unilateral renal denervation. Tubular reabsorption of sodium was less in the denervated kidney. Bykov and Alexeev Berkman (1930, 1931) (see Bykov, 1952) found that a conditioned 'water' diuresis in dogs may be partly inhibited by denervation of the kidneys

Renal blood flow was measured only in the experiments of Kaplan and Rapoport (1951), where the increased renal excretion of water and electrolytes after splanchnicotomy was independent of changes in renal blood flow. Our experimental results in patients with heart failure (see above) demonstrated a close relationship between changes in renal blood flow and tubular reabsorption of water and electrolytes

A partial answer to this question can be found in the experiments of Cort and Kleinzeller (1956) on isolated kidney tissues of rabbits. Changes in transport of cations and water were studied during two hours exposure of kidney slices to

... of sodium into the denervated slices during leaching at 0°, and a slower expulsion of sodium from the denervated kidney slices during the incubation period. The changes in water content of the slices were in the same direction as the shifts of sodium. The difference between

... accumulation during subsequent incubation slower in the denervated kidney

failure inhaling 50 per cent oxygen plus 4 per cent carbon dioxide for 30 minutes (Foldi *et al*, 1950). According to these authors renal changes are brought about by hypoxia in the brain.

It is improbable however that every case of heart failure is accompanied by cerebral hypoxia. The renal changes are manifested, as shown above, in left sided failure. The results of Scheinberg (1950) indicate a decreased blood flow through the brain in heart failure together with a rise in cerebral vascular resistance. If the cerebral supply of oxygen is really insufficient we might expect quite the reverse, a diminution of cerebral vascular resistance and an increase in cerebral blood flow. This was actually demonstrated in man during experimental hypoxaemia by Kety and Schmidt (1948).

We are of the opinion that the heart itself may be the starting point for the haemodynamic functional changes in heart failure and in all situations in which CO is inadequate for the requirement in tissues, i.e. where oxygen utilization in tissues increases (Fejfar 1956, 1957, 1958). The basis for this hypothesis will be briefly summarized.

(a) Myocardial utilization of oxygen is even with physical inactivity in healthy subjects greater than that by the other important organs of the body. A very rise in oxygen consumption or utilization in tissues (muscular effort, anaemia, mitral stenosis, etc.) is associated with coronary vasodilation, an increase in the coronary fraction of CO and vasoconstriction in the kidneys.

(b) We have demonstrated that during the inhalation of oxygen a normal CO in a healthy subject or in compensated patients either does not change or decreases while a low cardiac output in heart failure increases (Fejfar 1957, Fejfar *et al* 1958a).

(c) Gomori and co workers (1954) in experiments cited above did not find an elevation of CO during isolated hypoxia of the brain. On the other hand when the isolated head of a dog was perfused by arterial blood and the trunk supplied with hypoxaemic blood (the dogs inhaled a mixture with a low

balance studies, and by analyses of muscle biopsies, that in addition to the cellular loss of potassium there is an increment of sodium in cells (Iseri, Boyle and Myers, 1950, Iseri *et al*, 1952, Squires, Crosley and Elkinton, 1951a, Warner *et al*, 1952, Cort and Matthews, 1954, see also Elkinton and Danowski, 1955, Cort and Fencel, 1957) Particularly important is the fact that potassium depletion occurs in subjects treated by repeated injections of mercurial diuretics (Squires *et al*, 1951b, Cort and Matthews, 1954) In some of these severely ill cases hyponatraemia and hypochloraemia with an elevated concentration of bicarbonate may be observed

Clinical diagnosis of potassium depletion in chronic congestive failure is difficult to prove Decompensated cardiacs excrete negligible amounts of sodium and the stronger acid radicals are excreted neutralized by potassium Therefore the typical finding of a far higher concentration of potassium than sodium in the urine in congestive failure is not alone sufficient proof of cellular loss of potassium

Plasma levels of Na^+ , K^+ , and Cl^- are usually within the normal range in decompensated cardiac patients

Table I presents the relationship between plasma levels of Na^+ , K^+ and HCO_3^- and concentration of Na^+ and K^+ in muscle biopsy specimens in 13 patients with various degrees of heart failure Concentrations of total muscle Na^+ and K^+ are expressed in m equiv 100 g of fat free dry solids (FFDS) Normal values given by Cort (1955b) are about 13 ± 2 m equiv. of Na^+ and 45 ± 3 m equiv. of K^+

It will be seen that all the patients had a decreased amount of potassium in skeletal muscle This K^+ depletion was very marked although not all were treated with mercurial diuretics Patient W E was not yet in right sided failure In all patients with the exception of A Z, the plasma concentrations of Na^+ and K^+ were within the normal range In the majority the concentration of bicarbonate was slightly elevated None of them showed ECG changes typical of

In six rabbits with bilateral denervation the resting clearances of inulin and PAH were practically the same as in the rabbits without renal denervation (Brod and Sirota, 1949). Cort and Kleinzeller (1956) therefore conclude that the differences described are due to a direct nervous effect on tubular cells rather than to a change in renal blood flow.

It is difficult to compare results obtained from experiments with tissue slices or in anaesthetized animals, with results from human subjects, in which every disturbance of homeostasis is immediately compensated for in several ways. Neural and humoral regulation act simultaneously and it is practically impossible to differentiate them. It seems, nevertheless, that even in subjects with chronic heart failure, retention of electrolytes and water is the result of haemodynamic changes parallel with increased tubular reabsorption of sodium and water. These changes may be initiated by a reflex mechanism acting through adrenergic nerves. Increased secretion of aldosterone and ADH is a secondary manifestation. This secondary aldosteronism may, however, prevail in the long run, dominate the whole picture of chronic congestive failure, and close the vicious circle.

Further consequences of retention of salt and water in heart failure

The retained sodium and water in congestive failure does not enlarge the volume of extracellular fluid only. In patients recovering from heart failure the reduction of body weight was greater than the reduction in the amount of extracellular fluid (Seymour *et al*, 1942), chloride output (Schroeder, 1950) or sodium loss (Miller, 1950, 1951). Thus surplus water must come from cells. In the development of congestive failure, the water accumulates in both extracellular and intracellular compartments.

At the same time changes begin in the concentration of electrolytes. The loss of cellular water was described in 1930 by *et al*. It has been ascertained by

balance studies and by analyses of muscle biopsies, that in addition to the cellular loss of potassium there is an increment of sodium in cells (Iseri, Boyle and Myers, 1950, Iseri *et al*, 1952, Squires, Crosley and Elkinton, 1951a, Warner *et al* 1952, Cort and Matthews 1954, see also Elkinton and Danowski, 1955, Cort and Fencel, 1957) Particularly important is the fact that potassium depletion occurs in subjects treated by repeated injections of mercurial diuretics (Squires *et al*, 1951b, Cort and Matthews, 1954) In some of these severely ill cases hyponatraemia and hypochloroemia with an elevated concentration of bicarbonate may be observed

Clinical diagnosis of potassium depletion in chronic congestive failure is difficult to prove Decompensated cardiacs excrete negligible amounts of sodium and the stronger acid radicals are excreted neutralized by potassium Therefore the typical finding of a far higher concentration of potassium than sodium in the urine in congestive failure is not alone sufficient proof of cellular loss of potassium

Plasma levels of Na^+ , K^+ and Cl^- are usually within the normal range in decompensated cardiac patients

Table I presents the relationship between plasma levels of Na^+ , K^+ and HCO_3^- and concentration of Na^+ and K^+ in muscle biopsy specimens in 13 patients with various degrees of heart failure Concentrations of total muscle Na^+ and K^+ are expressed in m equiv 100 g of fat free dry solids (FFDS) Normal values given by Cort (1955b) are about 13 ± 2 m equiv of Na^+ and 45 ± 8 m equiv of K^+

It will be seen that all the patients had a decreased amount of potassium in skeletal muscle This K^+ depletion was very marked although not all were treated with mercurial diuretics Patient M E was not yet in right sided failure In all patients with the exception of V Z, the plasma concentrations of Na^+ and K^+ were within the normal range In the majority the concentration of bicarbonate was slightly elevated None of them showed FCG changes

Table I

RELATIONSHIP BETWEEN PLASMA LEVELS OF Na^+ , K^+ AND HCO_3^- AND CONCENTRATION OF Na^+ AND K^+ IN THE SKELETAL MUSCLE

MS—mitral stenosis; MI—mitral incompetence, Tri S—tricuspid stenosis, Tri ins—tricuspid insufficiency; H + I H D—hypertensive and ischaemic heart disease. See details in text.

| Name | Sex | Diagnosis | Age years | Degree of heart failure | Muscle | | Plasma | | | Note |
|------|-----|----------------------------|-----------|-------------------------|--|---|---------------|--------------|-----------------------------|------------------------|
| | | | | | Na^+ total m-equiv/100 g F.F.D.S. | K^+ total m-equiv/100 g F.F.D.S. | Na^+ | K^+ | HCO_3^- m-equiv/l. | |
| FČ | M | MS > MI
Tri S | 33 | 5 | 10.23 | 15.8 | 137 | 4.4* | 23.3 | |
| A S | F | Atr sept d f | 48 | 3-4 | 19.75 | 27.6 | 141 | 5.15 | 29.4 | 0 mercurial diuretic |
| M B | † | MS | 38 | 4 | 13.9 | 28.3 | 150 | 4.54 | 28.0 | |
| M T | † | MI > MS | 37 | 3 | 15.04 | 24.64 | 137 | 4.5 | 26.4 | 0 mercurial diuretic |
| I D | F | MS > MI
postcommis | 40 | 4 | 23.39 | 21.52 | 145 | 5.75 | 28.1 | 0 mercurial diuretic |
| M D | F | MI, bacterial endocarditis | 35 | 3 | 12.51 | 29.92 | 143 | 3.9 | 30.2 | 0 mercurial diuretic |
| E K | M | MS Tri S | 46 | 5 | 14.3 | 37.2 | 131 | 6.34 | 28.5 | |
| P U | M | MS Tri ins. | 43 | 5 | 27.1 | 25.46 | 144.1 | 4.56 | 28.1 | |
| A Z | M | MS
postcommis | 49 | 5 | 22.5 | 11.2 | 126.5 | 4.02 | 14.8 | 8th day post operative |
| A V | F | MS | 51 | 3 | 10.5 | 21.76 | 148.5 | 5.2 | 31.1 | |
| H Ch | F | MS
postcommis | 37 | 4 | 19.57 | 33.61 | 143.3 | 4.9* | 24.5 | |
| V B | M | H + I H D | 60 | 4 | 16.91 | 39.84 | 143.5 | 4.94 | 29.4* | * not at the same time |
| M V | F | MS
postcommis. | 37 | 3 | 20.78 | 34.04 | 141.5 | 4.44 | 26.8 | |

was found in patient A Z, with suppuration in the thoracic wound one week after mitral commissurotomy, 24 hours before death. He was by this time in severe metabolic acidosis. The loss of about three quarters of the muscle potassium was

the probability of being hit according to the number of times the object has been hit before, and if you proceed further and increase the speed of the shooting the mathematics develop in the direction of the Makeham curve and certain modifications of it

Maynard Smith I do not believe for one moment that the shape of these curves has anything to do with the organism that has been studied. I think it has something to do with the environment in which it was studied.

Perks I have thought about this problem for a long time and I believe the shape has something to do with time.

Tanner You would expect a different-shaped curve in a less long-lived organism?

Perks No. I think it is the cumulative factor in life: injuries and so on are additive or cumulative in almost a geometrical sense and you must expect to have exponentials coming into the form of the mortality rates.

Tanner Does this make the change then from the gamma function into the Makeham type of curve? You think that the reception state changes according to the number of shots impinging?

Perks Yes.

Holt In the models for fitting the depreciation of motor cars death is assumed to result from either single big accidents or an accumulation of small ones and a complex death curve follows: it seems to have some possible application to animal mortality.

Rotblat I am concerned to know what lifespan is because we have to express some of our findings in terms of lifespan. For example people often speak about the effect of radiation in causing a shortening of the span of life and they put down figures of the percentage of life shortening per rontgen. But everyone I have asked what he meant by the term lifespan gave a different answer. I was hoping that perhaps in this meeting we might come to some agreement on that. I was impressed by your remarks on the first day, Dr Benjamin, when you brought in what you called the senescence peak. This peak seems to me to be the quantity to put down as the normal lifespan. I was particularly interested to see data presented by various people which showed that although the shapes of the mortality curves may differ enormously nevertheless for a given species they all reach nearly the same end point. If we could draw the ideal curve, i.e. if we could eliminate all deaths due to accidents, infections etc. then the normal lifespan would be obtained immediately from the senescence peak. But in practice this will be very difficult because most mortality curves do not approximate to this ideal. We are therefore still left with the question of what we

ertain extent by the infantile mortality, and by mortality from
 ents and infections. If you reduced those mortalities, then, as a
 piece of arithmetic, the mode is advanced and the curve of

pendent.

Rockstein: I think we are being unrealistic about this. I would
 ggest that mean longevity seems to be a thing that you could

obtain
 concerned
 pare, why not use an animal, as you
 which you can get such data? I have been amazed that for
 generations in the housefly, for example, one can continue to get the
 same mean value. I say this value is a good basis for comparison in
 an experimental study. With the white rat, under specific laboratory
 conditions, for example, the only thing that will vary in irradiation
 is the dose or dosage of radiation. With humans we run
 into problems with life expectation

inbred lines of a number
 why the mean longevity is not as good a criterion
 it considers the accidental deaths, it considers the possible distur-
 bances that would have from having had early deaths or
 extended longevity

Perls: I am sure you are right. It is different
 problems require different solutions.

Rotblat: If we say, for example, that radiation causes a contraction
 of the scale of life, and suppose we are dealing with the ideal case in
 which all animals die of old age, then for the irradiated animals we
 would obtain a curve but bodily shifted to the left. This
 would be very different. It may be that
 radiat
 The
 actually
 lifespan.

the average is the first quantity
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 si
 ing
 of the survival curve are
 mental factors under investigation I have
 studies of radiation effects on mice, you could characterize the effects
 of the λ and the α parameter of the Gompertz
 radiation—to restate what I
 without a change in α . Con
 It is perfectly
 true that this Gompertz is an adequate des-
 cription of the life-tables of natural populations of it should be

borne in mind the
cussing general pr
expressions are us

$$q_x = \sum_{i=1}^n A_i e^{b_i(x)}$$

Perls. If you are fitting mathematical expressions to your data of statistical distribution, then clearly you estimate the parameters, and your estimated values for the parameters sum up the statistics. I thought the problem we were really talking about was how to characterize statistics for which you have not got a mathematical expression. For a single measure to be sufficient the distribution

can say is that for some purposes one measure may be better than another. You have to accept that the expectation of life or the half-

curve that you can really say that any parameters are better estimators than any others.

Benjamin. All this discussion of lifespan seems to be only a means to an end, we really want to get away from lifespans to considering the ageing effects, for example, of changes in environment. For that we really want two things. First, we need some kind of function

may make a difference between the curve bulging up one way, or bulging down the other. The largest possible dispersion of effects is found here, which brings us to the idea of the 50 per cent survival age point. To get a time scale which enables comparisons to be made between different kinds of animals, on the other hand, you need something which is not too sensitive. This suggests that you should use the height of the peak, although the height of the peak is very much correlated with the expected deaths and so on, the actual movement of the peak is not particularly sensitive. So while it is unprofitable to talk about an ideal lifespan, it is quite practical and profitable to look at large families of curves of death for the same species, and see what kind of shape they tend to in general, so that you can get for the different species a typical modal attained length of life, which you could use as the time scale.

Comfort: This is Bodenheimer's "physiological longevity" (Bodenheimer, I. S. (1938). *Problems of animal ecology*. Oxford: Blackwell).

Dr. Benjamin: You should all take an interest in this. I think it is a very good thing that all scientists should use the same notation if there is one which is generally accepted. Dr Benjamin has included some of it in his paper and I think it probably could be extended to cover all your needs.

We have heard the phrases lifespan and ageing over and over again but I do not think you will ever succeed in rigorously defining them. I think they are best left as rather vague concepts, as we know in general what we are talking about.

I have been a little puzzled by the extent to which logs have been taken of various observed figures. To me it only confuses the issues, particularly when you have a graph on a logarithmic scale, although I do understand that sometimes it is necessary to do that to compress the graph to reasonable dimensions. But there is no excuse for taking logs in arithmetic merely to get rid of some of the variations, and apparently to produce a correlation or regression which possibly is not there if you do not take logs. What does the logarithm of a residual mean? When you take a logarithm of the cephalization index and then associate it with a logarithm of body weight, and finally with a logarithm of a lifespan, what does it all mean?

Dr. Benjamin: The technique that might be useful for comparing the lifespans of animals in their natural habitats, but only if the animals are of the same species.

state So if you take the crude death rate over an interval of time, then a fair measure of the expectation of life, in terms of that interval, is the reciprocal of the crude death rate, provided that population is stationary, or nearly stationary. If it is not nearly stationary, you can probably make an approximate adjustment

The only other thing I want to say is that the actuary's use of life-tables is very different from yours. The life table is not an end in itself for actuaries, it is merely a step on the way from a set of

the calculation of premium rates, reserves,

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what Dr. Chitty has said I feel like withdrawing this comment,
because if in other species the probability of their dying in the field
increases with age, this is the fundamental thing. It comes back to

use an arith/log scale, arith for time and log for survival, so that constant mortality gives a straight line

Tanner I have been sitting here for the last half hour with a very strong feeling of *déjà vu*. The people who are interested in growth have been fitting growth curves with decreasing enthusiasm for about 35 or 40 years. It seems to me that you are pursuing a vertiginous and descending pathway.

I do not think there is anything in the general aspects of growth which leads one to suppose that the allometric relationship is very useful in general. There may be instances where it is necessary, not from any theoretical considerations but because using logs produces a straight line, I do not think that there can be any other justification.

Sacher A transformation such as the logarithmic cannot increase the amount of information contained in a set of data, so if the correlation of the transformed variables is 0.99+ this expresses a fact about the data, i.e. that only a fraction of a percentage of the total variance is error variance when the proper functional relation between the variables is found. No *a priori* justification is needed for the use of the power function. In my own and Brody's data there is no question about its appropriateness. The fact that some other data are adequately rectified by a linear plot is interesting but it cannot contravene the allometric relations as they have been established in many other cases.

Chitty My particular problem is to find out why animal populations in nature do not go on increasing indefinitely and what it is that they die of. Most people up to the present have considered that deaths in nature could be almost entirely accounted for through predation or epidemic disease, heavy infestation with parasites or food shortage, but it is now clear that this is a wholly inadequate explanation, particularly for the huge mortalities which occur in the young stages. The problem arises—what exactly is it that they die of? The suggestion was first made by P. H. Leshe and R. M. Ranson in 1940 (*J. Anim. Ecol.* 9, 27) for the field mouse that the life table type of explanation might be applied to field populations. In the laboratory you recognize that with age there is an increasing probability of death from a variety of causes which are peculiar to the particular environments—that is to say a group of mice in one laboratory would not have the same final causes of death as they would in another—but in each case there would be the common fact that as they grew older they became increasingly liable to die of whatever it was that was peculiar to those environments. The field evidence strongly suggests that this may be a profitable way of

looking at natural populations, too. The problem now becomes to try and find some general law which is applicable in spite of the fantastic variety of conditions in the field. I think one would never hope to find any common causes of death associated with the actual time of death in nature. Every environment differs in its hazards from every other one. The point is can we find anything in the properties of the animals which does obey some sort of general law under all these varied circumstances? In other words what is it that makes an animal increasingly likely to die regardless of what actually kills it in the end? We might divide the problem into both multiple and single processes. The final causes of death would be the multiple processes and there we have very little hope of introducing much unity but by concentrating on susceptibility there may be some hope of finding a common process which can equally well be studied in those animals which live to a great age in the laboratory and those which die at a much younger age in nature. Exactly how one goes about this I do not know and that is the point at which my work is hung up. I have to account for very violent changes in the probability of survival at different times of the population cycle, and exactly where does one go to look in the organism for something which may be an index of this change in properties? That seems to me to be very similar to the problems with which one is faced in trying to account for the increasing probability of death with age in man. It is like trying to find an age at which you can say that the probability of death is even at a much

and even at a much younger age in nature. The point is can we find anything in the properties of the animals which does obey some sort of general law under all these varied circumstances? In other words what is it that makes an animal increasingly likely to die regardless of what actually kills it in the end? We might divide the problem into both multiple and single processes. The final causes of death would be the multiple processes and there we have very little hope of introducing much unity but by concentrating on susceptibility there may be some hope of finding a common process which can equally well be studied in those animals which live to a great age in the laboratory and those which die at a much younger age in nature. Exactly how one goes about this I do not know and that is the point at which my work is hung up. I have to account for very violent changes in the probability of survival at different times of the population cycle, and exactly where does one go to look in the organism for something which may be an index of this change in properties? That seems to me to be very similar to the problems with which one is faced in trying to account for the increasing probability of death with age in man. It is like trying to find an age at which you can say that the probability of death is even at a much

Tanner There does not seem to me to be any connexion between the situation in non-domesticated animals and the situation in the human. All the other mammals and birds would have died early in terms of human growth. The human was the only animal which seemed to be surviving long enough to experience senescent processes. Cellular ageing might paradoxically have been closer to the situation in man than is the situation in the passerine for example. After what Dr Clutton has said I feel like withdrawing this comment because if in other species the probability of their dying in the field increases with age this is the fundamental thing. It comes back to

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senescence The nature of this grouping probably has some moral significance

A point that impressed me very much was the difficulty of evaluating the significance of data obtained from animals in captivity which are living in conditions of constant diet, no exercise constant illumination very little in the way of seasonal change, and so on, to which even animals which have been selected for laboratory purposes are not really 100 per cent adapted After all the period of adaptation to laboratory life is comparatively short compared with the period of evolution I do not really know what can be done about that What is outstandingly important is that wherever possible a pathologist should look at the animals when dead and this should be done for insects as much as for any other form of animal life.

The concept of a biological time scale continues to interest us though it is obviously even vaguer than some of the other concepts which, as Mr Perks remarked are better kept vague However, this particular one is of no use to us unless we can measure it It is useless to continue to use it without exact definition

Whatever the source if we exclude accidents to which the individual concerned does not contribute in most instances susceptibility to mortality in a species or a strain does develop in a typical manner It is perfectly true that it has been said that if one cause of mortality is eliminated we shall have had

data and we would have survived eliminating one cause of death is not functionally we appear to be dealing with a unitary process ageing is in fact unitary however cannot be determined from the data presented with so far I am not at all clear to the point of synchronization of individuals in a very

the energy one but of value at a rate this is open to study of We ought to use metabolic poison

what I was trying to say before, that just as in growth we talk about developmental age so we can talk about the probability of death in any given situation as developmental age further down the scale. If that is really true, if these analogies can be made the same in animals and man then we can use the results of both field workers and the experimentalists much more usefully to shed light on the human situation.

Comfort The figures we get for small mammals have often misled people into thinking that all mammals behave in this way. We have only very few figures for the larger ones but there is some evidence that many larger mammals in the wild achieve high ages quite often. I would be very surprised if some of the larger wild ungulates didn't live long enough to senesce. Wild horses if one had the chance of observing them may perhaps live to a fair proportion of the age reached by tame horses.

Sacher Porcupines can survive until they are so arthritic they can hardly climb trees—nobody comes up against them except mountain lions.

Verzár Dr Chitty did you imply that the time of survival for a certain species depends on the number of individuals living at the time? If you put a pair of fish in a pond they will have certain survival characteristics for their age. When the pond becomes full with fish the population will become constant. Then the individual survival curve will probably be different otherwise the number of fish would continue to increase which is impossible because there is not enough food.

Chitty The number alive has a very great influence on the survival rate but the survival time can certainly not be predicted from the numbers of the animals alone. One must also take into account the behaviour of the population. experimentally you can have a family group of 50 animals which is perfectly amicable and has a good survival rate yet with two animals in a similar space who are strangers the survival time of one of them will be about half a day. The presence of other hostile animals of the same sort is I think one of the strongest environmental factors which does affect survival regardless of the amount of food available.

* * * *

Danielli I shall not attempt in any way to summarize this meeting. I have been considerably refreshed by it in many ways. We have learned for example that man, skunks and porcupines are amongst the few animals who know how to survive into the period of

GROUP DISCUSSION

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A point that impressed me very much was the difficulty of evaluating the significance of data obtained from animals in captivity which are living in conditions of constant diet, no exercise constant illumination very little in the way of seasonal change and so on to which even animals which have been selected for laboratory purposes are not really 100 per cent adapted After all the period of adaptation to laboratory life is comparatively short compared with the period of evolution I do not really know what can be done about that. What is outstandingly important is that wherever possible a pathologist should examine animals when dead and this should be done for animal life

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desynchronize some of the processes which may be synchronized. It may be in this connexion that we could make some progress by studying systems in which one is normally dealing with symbiosis. Here the breaking-up of the symbiotic relationship might reveal phenomena which would be difficult to reveal by any other method.

A cellular approach to ageing would under certain circumstances facilitate examination of the actual process of ageing, if this is in fact to some degree unitary, but I am not convinced that this is so with higher animals. The ageing process in higher animals may be fundamentally a function of the complex of cells and operate at a higher level of organization than is present in cells.

Another point which we have not discussed yet but which we are probably all agreed upon is that it is quite possible that lifespan in man as we see it now, is an entirely accidental by-product of selection for breeding efficiently at a much earlier age and does not in any sense correspond to social needs of the moment. An accumulation of experience has become much more important or at any rate equally as important as physical vigour, therefore socially speaking there is a very good case for anything which will enable us to modify the expectation of life in a radical manner. Looking at this from the long term point of view I think the possibilities for so doing would in fact be good by chemical means provided ageing does in fact occur by a unitary process. If on the other hand it is due to a very large number of non unitary processes which do not have any common mechanism then I think the chemical approach to extension of lifespan is fraught with so many difficulties that it is hardly worth considering. To illustrate the order of magnitude which I would expect if there is a unitary process involved I would like to refer briefly to the rate of mutation or rather the rate at which damage is caused by radiation. It is of course a tenable hypothesis that somatic mutation is one way or another directly concerned with the ageing process. There are cells which are killed by a dosage of the order of 100 r there are other cells which require a dosage of 1 000 000 r to kill them. This difference of four orders of magnitude is not at present as far as I know accountable for in any cytological or physiological terms whatever. Therefore if ageing were associated primarily with somatic mutation or some other generalized mechanism of this type we might expect that under suitable conditions lifespans could be varied by that order of magnitude. This sounds a little like science fiction but all of us have seen so much of what we regarded as science fiction 20 years ago turning up as reality, that I think we must envisage the possibility that we may be able to make radical changes in lifespan.

GROUP DISCUSSION

My final comment is that I regard it as singularly unfortunate that so much of the research on cancer is conducted essentially without reference to the phenomena of ageing, of which I think it is a part. I believe that not only would a study of ageing benefit from more knowledge of what is going on in older animals, but the whole field of investigation might benefit equally, and perhaps far more. Thus for a considerable degree, at the moment, it is not possible to transplant the conditions—a thing which does not approach what happens in the average human patient. Prof. Muirhead's laboratory is a shining example of an institute where this isolation of cancer research from ageing research does not occur, but I hope it will not long continue to be one of the very few shining examples.

My final comment is that I regard it as singularly unfortunate that so much of the research on cancer is conducted essentially without reference to the phenomena of ageing of which I think it is a part. I think not only would a study of ageing benefit from more knowledge of the animals, but the whole field of cancer research is perhaps far advanced at the moment by the transplantation of tumours into young animals, then seeing what could be done in the way of inducing similar conditions—a thing which does not approximate very closely to what happens in the average human patient. Prof Mühlbock's laboratory is a shining example of an institute where this isolation of cancer research from ageing research does not occur, but I hope it will not long continue to be one of the very few shining examples.

APPENDIX

NOTE ON SOME MATHEMATICAL MORTALITY MODELS

R E BEARD

Pearl Assurance Co Ltd London

1 A satisfying basis for a law of mortality would be a formula that, starting from some fundamental concepts about the biological ageing process, led to a distribution of deaths by age which was comparable with observational data. Such comparison would not be simple and straightforward because environmental and secular factors would introduce distortions as compared with the theoretical underlying distribution.

2 In the course of numerical work extending over a number of years, on the expression of human mortality functions by mathematical formulae various attempts have been made by the writer to develop an approach on this basis. The results obtained have not led to any satisfying formulae but they are suggestive of different lines of approach and have been summarized below in the hope they may be of value to others interested in the subject. The note follows the sequence in which the ideas have developed in the mind of the writer and leads from considerations based on the force of mortality, μ_x , to those based on the curve of deaths μ_d .

3 The first mathematical expression which provided a reasonable representation of the observed force of mortality in human data was that first proposed by Gompertz (1825) and later modified by Makeham (1867). Basically the law was derived by postulating a relationship between the rate of change of the force of mortality at any age and its value at that age. The next significant modification to the Makeham law was the system of curves devised by Perks in 1932 and of which the important formula was the logistic. Many human life-tables have been graduated by this basic curve modified in some instances to allow for special features of the data particularly at the younger and early middle ages and the clear fact emerges that adult human mortality can be very well represented by a logistic curve of the form

$$\mu_x = A + B e^{ax} / (1 + D e^{ax}) \quad (1)$$

which will be

which it is

1939a, 1951a, 1951b, 1951c

Laves, 1956)

of the ordinate at age x of the curve of

frequency curves which can be used to represent the distribution of

morality rates as well as mortality rates -
p. 57 (Revised 1951b)

all those along with mortality rates -

time

Gompertz' law arises by using condition (c) only,

$$\text{i.e. } d\mu_x/dx = \lambda\mu_x \quad \text{whence } \mu_x = B e^{\lambda x}$$

Makeham's law arises by using conditions (a) and (c),

$$\text{i.e. } d\mu_x/dx = \lambda(\mu_x - A) \quad \text{whence } \mu_x = A + B e^{\lambda x}$$

Perks' law arises by using conditions (a), (b) and (c),
i.e. $d\mu_x/dx = \lambda(\mu_x - A)(E - \mu_x)/(E - A)$

$$\text{whence } \mu_x = A + \frac{(E - A) D e^{\lambda x}}{1 + D e^{\lambda x}} \quad (4)$$

The Perks (logistic) relation can be expressed as stating that the rate of change of μ_x is proportional to the product of its value and the amount by which it falls short of its upper limiting value.

8 If the requirement of a constant upper limit for the rate of mortality is relaxed other formulae can be developed on similar lines to those of the preceding paragraph. For example,

$$\frac{d\mu_x}{dx} = \frac{\lambda(\mu_x - A)}{1 + B(\mu_x - A)} \quad \text{gives } \mu_x e^{\lambda x} = C e^{\lambda x} \quad (5)$$

$$\text{where } \mu_x = B(\mu_x - A)$$

and

$$\frac{d\mu_x}{dx} = \frac{\lambda(\mu_x - A) \left(1 + \frac{D}{B} \mu_x - A\right)}{\left(1 + \frac{2D}{B} \mu_x - A\right)} \quad (6)$$

$$\text{gives } \mu_x = A + \frac{B}{2D} (-1 + \sqrt{1 + 4 D e^{\lambda x}})$$

Formula (6) is equivalent to a continued fraction form for μ_x , i.e.

$$A + \frac{B e^{\lambda x}}{1 + \frac{D e^{\lambda x}}{1 + \frac{B e^{\lambda x}}{1 + \frac{D e^{\lambda x}}{1 + \dots}}}}$$

and the relationship between formulae (2) to (6) is clearly seen by expanding the expressions for μ_x in terms of powers of $e^{\lambda x}$, i.e.

formula (2) gives $B e^{\lambda x}$

$$\text{" (3) " } A + B e^{\lambda x}$$

$$\text{" (4) " } A + B e^{\lambda x} - BD e^{2\lambda x} + BD^2 e^{3\lambda x} -$$

$$\text{" (5) " } A + B e^{\lambda x} - BD e^{2\lambda x} + \frac{1}{2} BD^2 e^{3\lambda x} -$$

$$\text{" (6) " } A + B e^{\lambda x} - BD e^{2\lambda x} + 2 BD^2 e^{3\lambda x} -$$

9 The differences between formulae (4), (5) and (6) will become apparent only at the old or very old ages and unless the data were extensive the differences would be unlikely to be significant for many numerical processes. From a scientific point of view the models are, of course, quite different.

10 An alternative approach to the question, but still based upon rates of mortality, is to determine the conditions necessary for μ_s to be a Perks (logistic) curve, given that the population can be stratified according to a longevity factor and that the basic mortality law is Makeham in form (Beard, 1952b). Thus let μ_s^* be the force of mortality at time (\equiv age) k for the group having longevity factor s and let $\phi(s) ds$ be the proportion of the initial population having factor s . Then the survivors of $\phi(s) ds$ at time k are

$$\phi(s) ds \exp\left(-\int_0^k \mu_s^* dt\right) \quad (7)$$

and the total survivors at time k

$$l_k = \int \phi(s) \exp\left(-\int_0^k \mu_s^* dt\right) ds \quad (8)$$

where the integral is taken over the whole range of s .

The force of mortality at time k ($= -d \log l_k / dk$) is then

$$\mu_k = \frac{\int \phi(s) \mu_s^* \exp\left(-\int_0^k \mu_s^* dt\right) ds}{\int \phi(s) \exp\left(-\int_0^k \mu_s^* dt\right) ds} \quad (9)$$

11 From formula (9) it will be noted that μ_k is a weighted mean of μ_s^* ($= \mu_s^*$ say). Since the number of lives with heavier mortality will diminish more rapidly than those with lighter mortality, \bar{s} will decrease with increasing k . If the basic mortality is Makeham in form then $d\mu_s^*/ds$ will show a slackening off at the higher ages, i.e. the sigmoid feature shown by a logistic curve. In order to meet practical conditions some limitations are necessary on the form of $\phi(s)$: the lower limit must be ≥ 0 , but the upper limit can be ∞ .

12 If it be assumed that $\phi(s)$ is a gamma function such that $\phi(s) ds = ks^{\nu} e^{-\nu s} ds$ ($0 \leq s < \infty$) and that the mortality function for $\phi(s)$ is $\mu_s = \alpha + \beta s e^{\nu s}$ we have

$$\mu_k = \frac{\int_0^{\infty} ks^{\nu} e^{-\nu s} (\alpha + \beta s e^{\nu s}) \exp\left(-\int_0^k (\alpha + \beta s e^{\nu s}) dt\right) ds}{\int_0^{\infty} ks^{\nu} e^{-\nu s} \exp\left(-\int_0^k (\alpha + \beta s e^{\nu s}) dt\right) ds} \quad (10)$$

which reduces to

$$\mu_k = \alpha + \frac{(p+1)\beta\lambda e^{\lambda k}}{(\gamma\lambda - \beta) + \beta e^{\lambda k}} \quad (11)$$

which is a Perks (logistic) form

13. The results of the immediately preceding paragraphs are interesting in that the limiting value of μ_k arises from the manner in which the "mixed" population runs off. They have a certain appeal in that they are based on the assumption that the population is not homogeneous in regard to a mortality (or longevity) factor and that the mortality for an individual group continues to increase indefinitely. The limiting value of $\mu_k - \alpha$ as $k \rightarrow \infty$ from formula (11) is $(p+1)\lambda = 4\lambda/\beta_1$ where β_1 is the Pearson moment function of $\phi(s)$. For human lives $\mu_k \sim 0.6$ at the limit according to one fairly recent mortality table and $\lambda \sim 0.1$ so that $\beta_1 \sim 0.67$ i.e. a skew distribution with a tail towards the higher values of s . If s is a heredity factor, then stability of $\phi(s)$ over generations would imply fertility rates negatively correlated with longevity otherwise the shorter reproductive period of those with higher values of s would lead to a falling average value of s in the population. It is an interesting coincidence that the distribution of married women according to number of children born has a β_1 coefficient of the order of 0.7 (Papers of Royal Commission on Population 1950).

14. The assumption of other forms for $\phi(s)$ in formula (9) leads to other forms for μ_k which can have the appropriate shape but which are not convenient mathematically and no experiments have been made in this direction.

15. From the point of view put forward in paragraph 1 formula (10) suffers from the objection that it is based on the assumption of a Malthusian law, and is thus basically empirical. A further approach to the question is to build up models based on the so called "shot hypothesis" in which individuals are assumed to be subject to random firings and are assumed to die when they have been hit a specified number of times. Two main types of model have been investigated, which are referred to below as the "forward" and "backward" models respectively. In the forward model hits are assumed to accumulate and death to occur when the total reaches a certain figure. In the backward model the individual is assumed to start with a quota of units which are progressively lost in time death occurring when the total remaining falls below a certain figure.

16. The simplest forward model is derived by assuming that the

chance that an individual is hit in an interval dt is p ; this leads to a difference-differential equation

$$\frac{dl_t^2}{dt} = -pl_t^2 + pl_{t-1}^2 \quad (12)$$

where l_t^2 represents the number at time t who have been "hit" α times. If l_0 is the number of individuals at time 0 then a solution of equation (12) is

$$l_t^2 = l_0 e^{-pt} (pt)^{\alpha} / \alpha! \quad (13)$$

If the number of hits causing death is r , then the survivors at time t are

$$l_t = l_0 e^{-pt} \{ 1 + (pt)/1! + \dots + (pt)^{r-1}/(r-1)! \}$$

and the deaths in the interval t to $t+dt$

$$\mu_t l_t = l_0 e^{-pt} p t^{r-1} / (r-1)! \quad (14)$$

The force of mortality at time t is

$$\begin{aligned} \mu_t &= \frac{p t^{r-1}}{(r-1)!} \left/ \left\{ 1 + \frac{pt}{1!} + \dots + \frac{(pt)^{r-1}}{(r-1)!} \right\} \right. \\ &= p e^{-pt} (pt)^{r-1} \int_0^\infty e^{-x} x^{r-1} dx \end{aligned} \quad (15)$$

Formula (15) shows that the curve of deaths is an incomplete gamma function, or a Pearson type III curve. μ_t has the value 0 for $t=0$ and asymptotes to a value p at $t=\infty$ (Beard, 1939b).

17 A more natural function than μ_t in the present context is to use the function which bears the same relationship to $\mu_t l_t$ as μ_t does to l_t , i.e.

$$\frac{d(\log \mu_t l_t)}{dt} = \frac{1}{\mu_t} \frac{d\mu_t}{dt} - \mu_t$$

and from formula (14) we find this to be

$$\frac{d(\log \mu_t l_t)}{dt} = -p + \frac{r-1}{t} \quad (16)$$

18 Attempts to use the formula of paragraph 16 on human mortality data have been unsuccessful, the shape of $d(\log \mu_t l_t)/dt$ not

which reduces to

$$\mu_k = \alpha + \frac{(p+1)\beta\lambda e^{k\lambda}}{(\gamma\lambda - \beta) + \beta e^{k\lambda}} \quad (11)$$

which is a Perks (logistic) form

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15. From the point of view put forward in paragraph 1 formula (10) suffers from the objection that it is based on the assumption of a Malthusian law and is thus basically empirical. A further approach to the question is to build up models based on the so called "shot hypothesis" in which individuals are assumed to be subject to random firings and are assumed to die when they have been "hit" a specified number of times. Two main types of model have been investigated which are referred to below as the "forward" and "backward" models respectively. In the forward model hits are assumed to accumulate and death to occur when the total reaches a certain figure. In the backward model the individual is assumed to start with a quota of units which are progressively lost in time death occurring when the total remaining falls below a certain figure.

16. The simplest forward model is derived by assuming that the

APPENDIX

the solution of which leads to

$$l_t^z = l_0 e^{-p(\omega-t)} \{p(\omega-t)\}^{\alpha}/\alpha!$$

(23)

from which

$$\frac{d(\log \mu_t l_t)}{dt} = p - \frac{\alpha-1}{\omega-t}$$

if the deaths occur at the α th hit. In this formula $p \sim 0.3$, $\alpha \sim 11$ and $\omega \sim 110$ for human mortality.

22 No obvious physical model applies to equation (22), but the relationship can be written in the backward form

$$\frac{dl_t^z}{dt} = -\frac{\alpha}{\omega-t} l_t^z + \frac{\alpha+1}{\omega-t} l_t^{z+1} \quad (24)$$

in which the rate at which a unit is lost is proportional to the number of units remaining divided by the years of life remaining to the final age ω . From a biological point of view the concept of a final age by which the organism must be dead is unsatisfactory, but the fact that satisfactory numerical results arise only from a backward formula suggests that a closer study of this type of model might be more profitable.

23 The simplest backward model arises from the relationship

$$\frac{dl_t^z}{dt} = -p l_t^z + p l_t^{z+1} \quad (25)$$

where the organism is assumed to lose a unit at rate p . This has a solution

$$l_t^z = l_0 e^{-pt} (pt)^{n-z} / (n-z)! \quad (26)$$

where n is a maximum number of units. If death is assumed to occur when the number of units falls below r , we have

$$\frac{d(\log \mu_t l_t)}{dt} = -p + \frac{n-r}{t} \quad (27)$$

This is of similar form to equation (16) and is not suitable for human data.

24 By assuming that the rate of loss of a unit is proportional to the number of units remaining the relation

$$\frac{dl_t^z}{dt} = -p(\beta+z) l_t^z + p(\beta+z+1) l_t^{z+1} \quad (28)$$

fitting well to observed values which show a negative second differential coefficient over the adult ages.

19. As an extension of formula (12) a model can be set up in which the "hits" in an interval can be single, double, etc., in known proportions. The basic relation then takes the form

$$\frac{dl_i^x}{dt} = -pl_i^x + p \sum_{r=1}^x f(r) l_i^{x-r} \quad (17)$$

This can be integrated to

$$l_i^x = e^{-pt} \int p e^{pt} \sum f(r) l_i^{x-r} dt \quad (18)$$

bility of a "hit" is dependent on the number of "hits" recorded already. We then have the following

$$\frac{dl_i^x}{dt} = -(\beta + px) l_i^x + (\beta + p(x-1)) l_i^{x-1} \quad (19)$$

This can be integrated to give

$$l_i^x = l_i e^{-(\beta+px)t} \left(\frac{\beta}{p}\right) \left(1 + \frac{\beta}{p}\right) \left(x-1 + \frac{\beta}{p}\right) (e^{pt} - 1)^x \quad (20)$$

with

$$\frac{d(\log \mu_i l_i)}{dt} = -(\beta + x - 1)p + \frac{(x-1)p e^{pt}}{e^{pt} - 1} \quad (21)$$

Here again the form of equation (21) does not accord with observations from human data.

21. In the attempts to fit these forward type formulae to human data it was found (Beard, 1930, 1952c) that satisfactory numerical results could be obtained by expressing $\mu_i l_i$ in gamma function form subject to a terminal age ω , i.e. the infinite tail of the curve is the opposite way round to what would be considered natural. This formula, after elimination of a constant element representing accidental mortality, can be derived from the difference differential equation

$$\frac{dl_i^x}{dt} = pl_i^x - p_i^{x-1} \quad (22)$$

27 Calculation of the moments of the distribution of deaths by age for a population of mice (Greenwood, 1928) shows that a Pearson type III (gamma function) would give a fair representation, but, as with the human data, the curve is the "opposite way round", i.e. subject to a terminal age. By inference the Perls (logistic) curve would give a fair representation of this data. No calculations have been made on animal data or on physical objects such as electric light bulbs and motor cars (e.g. Cramer, 1958) but it would seem worth while trying to find out if observed data of this latter type would distinguish between the two types of processes.

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may be set up. This has the solution

$$l_t^2 = k e^{\alpha t} / (1 + D e^{\alpha t})^{\beta + \alpha + 1} \quad (29)$$

If death occurs when the units fall below α , we have

$$\begin{aligned} l_1 &= \sum_a l_t^2 = k / (1 + D e^{\alpha})^{\beta + \alpha} \\ &= l_0 D (1 + D)^{\beta + \alpha} / (1 + D e^{\alpha})^{\beta + \alpha} \end{aligned} \quad (30)$$

We also have

$$\frac{d(\log \mu_t l_t)}{dt} = p - \frac{(\beta + \alpha + 1) p D e^{\alpha}}{1 + D e^{\alpha}} \quad (31)$$

and

$$\mu_t \approx \frac{p(\beta + \alpha) D e^{\alpha}}{1 + D e^{\alpha}} \quad (32)$$

We have now found a difference equation model which leads to a Perks (logistic) formula for μ_t . In formula (31) the upper limit of μ_t is $p(\beta + \alpha)$, $p \sim 0.1$ and the limit ~ 0.7 so that $(\beta + \alpha) \sim 7$.

25. The distribution of α in the population at age 0 implied by equation (29) is a decreasing geometrical progression i.e.

$$\frac{D}{1 + D}, \frac{D}{(1 + D)^2}, \frac{D}{(1 + D)^3}, \dots$$

For human mortality D is small (of the order of 10^{-4}) so that the distribution is very slowly decreasing with increasing α .

26. The significant result which emerges from the experiments made along these lines is that to provide results which have some reasonable semblance to observed human mortality the backward type of model has to be adopted. This is consistent with death being regarded as the culmination of a degenerative process such that death occurs when the organism reaches a certain level of degeneration. The mathematical models are based on numerical results for adult ages and interpolation back to birth is possibly a questionable process, a more suitable approach being to regard the life and death process as a period during which the organism is building up to a complex situation with a subsequent degeneration. This would lead to models in which the whole of life process would be looked upon as the resultant effect of two opposing forces.

APPENDIX

27 Calculation of the moments of the distribution of deaths by age for a population of mice (Greenwood, 1928) shows that a Pearson type III (gamma function) would give a fair representation, but, as with the human data, the curve is the "opposite way round", i.e. subject to a terminal age. By inference the Perks (logistic) curve would give a fair representation of this data. No calculations have been made on animal data or on physical objects such as electric light bulbs and motor cars (e.g. Cramer, 1958) but it would seem worth while trying to find out if observed data of this latter type would distinguish between the two types of processes.

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AUTHOR INDEX

Plain numbers and date a contribution either in the form of an article or as a contribution to the discussions Italic numbers and date a reference to an author's work

| | | | |
|--------------------|--|--------------------|----------------------|
| Aasen O | 149 156 174 | Beveston R. J. H. | 142, 149 151 |
| Akyaz, E. | 149 174 | | 153 175 177 178 179 |
| Ally M. S. | 255 264 | Bezem, J. J. | 226, 227 229 |
| Alm G. | 144 155 159 | Bidder G. P. | 97, 103 |
| | 168 174 | | 173 175 182 189 |
| d'Ancona, U. | 167 174 | | 190 191 207 |
| Andersen J. | 92 94 95 102 | Blawicz, S. | 277 281 |
| Anderson J. | 232 234 241 | Blackburn M. | 146 149 151 175 |
| Andrew W. | 248 264 | Blair W. F. | 96 102 |
| Ansell S. | 21 31 | Blazka P. | 170 175 |
| Appelget, J. | 153 174 | Boedenheimer F. S. | 294 |
| Armbruster L. | 232 241 242 | Botcher T. | 60 61 69 |
| Arora, H. L. | 149 174 | Bor n, G. von | 119 123, 128, 132 |
| Ascher K. R. S. | 255 259 264 | Boroughs H. | 170, 175 |
| Asgood H. S. | 251 264 | Boyd H. | 70 84 91 96 102 |
| Austin O. L. | 98 102 | | 103 104 105 112, 113 |
| Auslun O. L. Jr. | 98 102 | | 119 132 137 217 225 |
| | | | 227 228 245 |
| Back E. | 233 238 241 | Boyd H. | 101 102 |
| Bagenal T. B. | 192 193 200 201 | Breder C. M. | 212 217 218 225 |
| | 202 205 207 | Brethrick O. | 237 243 |
| Bard D. | 33 | Brody S. | 124 132 |
| Banfield A. W. F. | 92 102 | Brown C. J. D. | 168 175 |
| Barcroft J. | 133 | Brown M. E. | 147 148 149 175 |
| Barnes, L. L. | 251 264 | | 217, 225 |
| Barnet, H. A. R. | 5 15 | Bryer A. M. | 138 |
| Barton R. A. | 53 54 | Buchanan A. D. | 59 69 |
| Bauer K. | 59 69 | Busher G. E. | 258 264 |
| Beard R. E. | 4 14 288 289 302, 303 305 307 308 | Burd A. C. | 149 175 |
| | 311 | Burns, C. M. | 21 31 |
| Beeson M. | 21 31 33 53 54 | Butler C. G. | 217 241 243 |
| Be Jing, D. L. | 197 207 | Buxton P. A. | 240 241 |
| Bell F. H. | 151 177 | | |
| Bendall J. F. | 101 102 | Cameron J. W. McB. | 258 264 |
| Benedict | 124 | Cannon C. | 59 69 |
| Beneke R. | 110 112 | Carlson L. D. | 89 |
| Benjamin B. | 2 15 16 17 18 19 | Chalmers, T. A. | 56 |
| | 32 34 70 293 | Chang, H. W. | 143 146 153 175 |
| Berdegue J. | 153 175 | Chapman W. A. | 170 175 |
| Berg B. N. | 16 32 33 72 73 | Chitty D. H. | 105 296 298 |
| | 74 75 76 79 79 80 82, 83 84 85 86, 87 88 114 | Chuganova M. | 33 54 |
| | 137 165 266 285 | Ciba Foundation | 128 132 |
| Berg L. S. | 212 225 | Clark, F. N. | 149 153 175 |
| Bertalanffy L. von | 157 169 175 | Clark H. W. | 212 226 |
| Bertholf L. M. | 235 241 | Clarke | 266 |
| Bertin L. | 168 175 | Clarke J. M. | 278 281 |
| Best, A. T. | 104 | Clarke, R. D. | 4 5 6 7 8 10 11 |
| Beutler R. | 235 236 241 | Cohen, D. M. | 14 15 |
| | | Cohrs, P. | 151 175 |
| | | | 110, 112 |

| | | | |
|-----------------|---|--------------------|---|
| Heimanek, J | 235 237 242 | Kuhn W | 240 242 |
| Hema, J | 227 | Kuiken, A | 237 243 |
| Herald, E. S | 155 176 | Kuznetsova G | 53 54 |
| Herrington, W C | 151 177 | | |
| Hervey G F | 227 | | |
| Hess, G | 235 242 | | |
| Hickey J J | 97 101 102 | Lack D | 97 101 102 104 |
| Helling, C F | 195 196 205 207 | Lansing A J | 259 264 |
| Hic, R. | 151 176 | Lark a P A | 182 208 |
| Hilton H E | 34 112, 243 245, 246 284 | Lavo p erre, M M J | 245 285 |
| Hin on S | 191 217 219 225 | Lea, E. | 145 149 176 |
| Hodge C F | 248 264 | Leshner S | 80 |
| Hoffman H | 237 243 | Leslie P H | 296 |
| Hogreve, F | 64 65 69 | Levin M D | 232 236 242 |
| Ho mrs, S J | 21 31 | Levinson Z. H | 255 259 264 |
| Holt, S J | 86 134 142 149 151 155 158 167 175 176, 178 179 209 210 226 227 228 229 246 290 | Lieberman H M | 250 251 255 256 257 258 260 264 |
| Hoogendoorn D | 21 31 | Lindauer M | 233 242 |
| Hubbs, C L | 146 155 176 | Lindop, Patricia J | 113 136, 138 141 |
| Hunter W R | 179 | Lorenz, E | 89 |
| Huxley J | 104 | Lotmar M | 232 233 234 242 |
| Hynes, H B N | 153 156 176 | Louveaux J | 236 242 |
| Hyttén F E | 33 | Luecke R W | 237 243 |
| Ioukas T | 248 264 | | |
| Irwam J O | 37 54 | McCay C M | 169 176 251 252 253 264 265 268 |
| Isupov A P | 53 54 | McCracken, F D | 151 175 |
| Ilev V S | 166 207 208 | McFadyean J | 50 54 |
| | | McGregor E. A | 192 208 |
| Jackson B H | 89 | McHugh T | 105 |
| Jala sto Eeva | 16 17 21 21 31 31 32 33 81 113 266 168 176 | McKeown, T | 29 31 |
| Jenk ns, R | 243 | MacMahon, L | 21 31 |
| Johansson A S | 237 242 | Madr A | 191 208 |
| John M | 261 281 | Mackintosh, J | 21 31 |
| Jones, E C | 153 156 176 | Makeham W M | 2 4 15 302 311 |
| Jones J W | 212 226 | Mannes, A. | 59 60 69 |
| Jordan D S | 193 208 | Margetts A R. | 151 176 |
| June F C | 43 54 | Murlow H | 63 69 |
| Kad e M | 96 102 | Marr J C | 153 176 |
| Kalabouchov N I | 186 208 | Marun W | 59 64 69 |
| Karzenk n G S | 196 197 208 | Matsumoto K | 43 54 |
| Katz, M | 145 151 176 | Mauermayer G | 232 234 242 |
| Kennedy W A | 56 56 70, 105 114 | Maurizio, Anna | 231 232 234 235 236 238 242 243 244, 245 246, 248 254 264 |
| Kershaw W E | 245 267 285 | Maynard, L A | 183 208 251 264 |
| | | Medawar P B | 271 281 |
| King, G | 10 | Mellen, I | 217 226 |
| King, J O L | 36 | Mendon M D | 149 176 |
| Kluwer H N | 99 102 | Menzel, D W | 183 184 185 208 |
| Knox G | 21 31 | | |
| Koch A | 236 238 242 | Minsky G I | 210 |
| Kocher V | 237 242 | Miller R B | 201 208 |
| Kocher A | 232 242 | Miner J R | 168 176 |
| Kong g A | 61 62 69 | Miser R W | 267 |
| Konop nsk | 67 69 | Moltoni, E | 53 54 |
| Kra ky I | 232 236 242 | Moore H L | 103 |
| Krause C | 110 112 | Morgulis, S | 155 176 |
| Krohn, P L | 271 281 | Morris, J N | 186 208 |
| Krumholz, L. A. | 171 176, 187 188 208 | Moskovich, V | 21 31 |
| | | Muhlbeck, O | 234 242 |
| | | Mune A | 33 71 80 287 |
| | | Murphy D P | 54 92 102 |
| | | Mussbacher A. | 262 264 235 238 242 |

- Comfort, A 17, 17, 32, 34, 35,
36, 37, 43, 44, 47, 52, 53,
54, 55, 56 70 71, 84, 85,
87 88, 103, 104, 113, 114
116, 117, 119, 132, 134
136, 137, 169, 173, 175
178, 179, 208, 208 209
210, 217, 225, 227 229
230, 244, 262 264 265
266, 286, 286 289 291
294 295 298
144 153 176
- Cooper E L 245
Corkins C L 119 123 132
Count, E W 169 176 251 253
Crowell M F 264
Crozier W J 267
Curtis 87
- Daly, C 21 31
Danielli J F 1 15 17 19 32 33
34 70 103 104 114 133
136 137 177 178 209
229 230, 281 282 298
92 94 103
- Dasmann R F 72
Davey W P 95 102
Davies, D F 192 207
Davis D E 151 176
Davis W S 159 175
Deason H J 91 102
Deelder C L 67 69
Deeley E S 149 175
Detkens 151 175
Devold F 60 69
Dickie L M 169 176
Dietrich H 63 69
Dille, W E 208
Dinkhauser F 121 112
Doljanski F 85
Dubois, E 175
Duetz, G H
Dymond J R
- Edmonds S J 169 175
Eidrigewits E V 53 54
El Deeb A L A 212 234 241
Ekin, R 168 176
Ellis, R S 248 264
Engeler, W 59 69
Erickson D W 196 197 207
Eschmeyer P H 197 207
Evans, C A 297
Evans, H 92 102
Evenius C 212 241
Evermann B W 212, 226
- Fahr H O 110, 112
Failla A 289
Farner D S 97 101 102 103
Farr, W 9
Farran, G P 194, 207
Farrar, C L 232 234 241
Feldman Muhsam B 259 264
Finnell, J 168, 176
- Fitch, H S 96, 97, 102
Fitch, J E. 155, 175
Flade, J E. 66, 69
Flower S 119, 128, 132 168 175
217, 225
- Foerster, R E 151, 156, 175
Fox H 108, 109, 112
Franca P da 153 175
Franko P 62, 69
Frankland H M T 53, 54
Franz, V 202, 207
Fraser E A 189, 207
Freudenberg F 62 69
Freudenstein H 211 236 237 241
Freudenstein K 232 241
Frost W E 153 175
Fry D H 168 170 175
Fry F E J 192 207
- Gardiner E M 21 31
Gardner E 248 264
Geiser S W 167 175 177
Gerking S D 18 79 171 171
179 180 181 181 207
209 210 211 228 229
230 265 284 289
- Gerner K 63 69
Gibson J R 29 31
Gilbert C S 245
Gompertz B 2 15 72 79 102 111
Gontarski H 212 241
Gordon J I 21 41
Gottlieb I 149 175
Grainger I H 147 153 175
Green R G 297
Greenwood M 111
Griffiths J T 277 281
Groot A P de 211 236 237 238
241
- Grosch D S 215 264
Grüneberg H 19 20 79 80, 283
Gumbel I J 117 112 134
Gunter, G 167 175
- Hafler I 196 208 218 225
226
- Hagel L 59 69
Hald A 120 131
Haldane J B S 53 54
Hall D A 111
Hansen F 59 69
Hanyu I 151 175
Harrison C R 71 79
Harrison J L 95 96 102
Hart J I 144 151 155 175 176
Hart J S 170 175
Hartmann W 59 69
Hartwig, W 56 57 65 66 67
69 70 71
Hatas S 248 264
Haydak, M H 232 236 237 238
239 241 242, 253
264
- Heady, J A 21 31

| | | | |
|-------------------|------------------------|--------------------|----------------------|
| Heimanek, J | 235 237 242 | Kuhn W | 240 242 |
| Hema, J | 227 | Kuiken A. | 237 243 |
| Herald E. S. | 155 176 | kuznetsova G | 53 54 |
| Herrington, W. C. | 151 177 | | |
| Hervey G F | 227 | | |
| Hesa, G | 235 242 | Lack, D | 97 101 102 104 |
| Hickley J J | 97 101 102 | Lansing A I | 259 264 |
| Hickling, C F | 195 196 205 207 | Larkin P A | 182 208 |
| Hic R. | 151 176 | Lavoipierre, M M J | 245 285 |
| Hinton, H E. | 34 112, 243 245 | Lea, E. | 145 149 176 |
| | 246, 284 | Leshner S | 80 |
| Hinton S | 191 217 219 225 | Leslie P H | 296 |
| Hodge, C F | 248, 264 | Levin, M D | 232 236 242 |
| Hoffman H | 237 243 | Levinson Z H | 255 259 264 |
| Hogrefe, F | 64 65 69 | Lieberman H M | 250 251 255 256 |
| Holmes, S J | 21 31 | | 257 258 260 264 |
| Holts, S J | 86 134 142 149 151 155 | Lindauer M | 233 242 |
| | 158 167 175 176 178 | Lindop Patricia J | 113 136 138 141 |
| | 179 209 210 226 227 | Lorenz, E. | 89 |
| | 228 229 246 290 | Lotmar M | 232 233 234 242 |
| Hoogendoorn, D | 21 31 | Louveau, J | 236 242 |
| Hubbs, C L. | 146 155 176 | Luecke R W | 237 243 |
| Hunter W R. | 179 | | |
| Huxley J | 104 | | |
| Hynes, H B N | 153 156 176 | McCay C M | 169 176 251 252 |
| Hytten F E | 33 | | 253 264 265 268 |
| | | McCracken F D | 151 175 |
| Ishikawa, T | 248 54 | McFadyen, J | 50 54 |
| Irwin J O | 37 54 | McGregor E. A | 192 208 |
| Izupov A P | 53 54 | McHugh, T | 105 |
| Izov V S | 186 207 208 | McKeown, T | 29 31 |
| | | MacMahon, L. | 21 31 |
| Jackson B H | 89 | Määr A | 191 208 |
| Jalaisto Eeva | 16 17 21 21 31 31 | Mackintosh J | 21 31 |
| | 32 33 81 113 266 | Makeham, W M | 2 4 15 302 311 |
| Jenkins, R | 168 176 | Mannes A | 59 60, 69 |
| Johansson A S | 243 | Margetts, A. R | 151 176 |
| John M | 237 242 | Marlow H | 63 69 |
| Jones E C | 261 281 | Marr J C | 153 176 |
| Jones, J W | 153 156 176 | Martin, W | 59 64 69 |
| Joëan D S | 212 226 | Matsumoto K | 43 54 |
| June F C | 193 208 | Mauermayer G | 232 234 242 |
| | | Maunzio, Anna | 231 232 234 235 |
| Kadé, M | 43 54 | | 236 238, 242 243 244 |
| Kabouchov N I | 96 102 | | 245 246, 248 254 264 |
| Karznik N G S | 186 208 | Maynard, L A | 183 208 251 264 |
| Katz, M | 196 197 208 | Medawar P B | 271 281 |
| Kennedy W A | 143 151 176 | Mellen I | 217 226 |
| Kershaw W E | 56 56 70 105 114 | Menon M D | 149 176 |
| | 245 267 285 | Menzel D W | 183 184 185 208, |
| King, G | 10 | | 270 |
| King J O L | 56 | Minsky G I | 201 208 |
| Kluene H N | 99 102 | Miller R B | 168 176 |
| Knox, G | 21 31 | Minter J R. | 267 |
| Koch A | 236 238 242 | Minter R W | 53 54 |
| Kocher V | 237 242 | Moltoni E | 103 |
| Kocher A | 232 242 | Moores H L. | 153 176 |
| König, K | 61 62 69 | Morgulis, S | 186 208 |
| Konopnik | 67 69 | Morris, J N | 21 31 |
| Kraus F | 252 236 242 | Moskovič, V | 234 242 |
| Krause C | 110 112 | Mühlbock, O | 33 71 80 287 |
| Krohn P L. | 271 281 | Mune A. | 54 92 102 |
| Krumholz, L. A. | 171 176, 187 188 | Murphy D P | 262 264 |
| | 208 | Mussbacher A. | 235 238 242 |

| | | | |
|-----------------|-----------------|---------------------|---------------------|
| Sonneborn T M | 32 35 53 54 | Verzár F | 82, 85 86 112, 133 |
| | 262 264 | Vill V O | 137 138 141 298 |
| Soudék S | 235 243 | Vives F | 35 43, 46 49 54 |
| Southern, H N | 101 103 | Viv no E | 149 177 |
| Spe i ng G | 251 264 | VNIRO | 237 238 242 243 |
| Sptakaya T D | 53 54 | Voogd S | 149 177 |
| Spobde, R | 64 69 | | 237 243 |
| Spurway H | 276, 281 | Wahl O | 235 243 |
| Stevens, C F | 21 31 | Walford L. A | 159 177 214 226 |
| Stockklausner P | 59 69 | Walker E. P | 119 133 |
| Stolbo a, A | 53 54 | Wallace, B. | 20 |
| Strawn K. | 153 176 | Wallace W | 189 208 |
| Suau, P | 149 177 | Weaver N | 237 243 |
| Summers-Smith D | 99 101 103 | Webb C. S | 104 |
| Sundnes, G | 169 176 | Weber R | 43 54 |
| Suier J | 21 31 | Weidenreich F | 134 |
| S. J. J. J. J. | 171 176 182 190 | Weinauer E | 104 |
| | 208 | West A. S | 258 264 |
| Svoboda, J | 235 243 | Weyer F | 234 243 |
| de Syl a, D | 235 173 228 | Weygand F | 237 243 |
| Snildard L | 19 129 133 289 | White, P | 267 |
| | | Wigglesworth V B | 87 133 240 |
| Tabah L. | 21 31 | | 243 243 245 267 285 |
| Taber R D | 92 94 103 | Wilkes, A | 258 264 |
| Tanster M L | 136 | Wilson I | 21 31 |
| Tanner J M | 84 85 86 88 266 | Winnigstedt, R | 59 69 |
| | 290 296 297 | Wirner S H | 237 243 |
| Tanquary M C | 232 242 | Wohlschlag, D E | 145 151 177 |
| Tauber O E | 277 281 | Woke, P A | 255 264 |
| Taylor C C | 149 167 177 | Wolkoff K | 110 112 |
| Templeman W | 146 151 177 | Walstenholme G E, W | 71 |
| Terpenn ng, J G | 182 203 | Wright, N C | 59 69 |
| Tester A L | 149 177 | Wurzel W | 59 69 |
| Thiele T N | 3 15 | Wussow W | 66, 67 69 |
| Thompson W F | 151 177 | Wynne-Edwards V C. | 193 194 |
| Thomson A M | 33 | | 195 208 |
| Tibbo S N | 149 177 | Yerkes, A. | 119 133 |
| Tews, K | 155, 177 | Yerkes, R | 119 133 |
| Todd F E | 237 243 | Yerushalmy J | 21 31 53 54 |
| Townsend C H | 217 226 | Yockey H P | 129 133 |
| Tracey K M | 262 264 | Yokota, T | 155 163 177 |
| Tucker D W | 174 177 | | |
| | | Zahl, P A | 267 |
| Vaa, K F | 170 177 | Zamyatin N | 53 54 |
| Vallo s, H V | 134 | Zander E | 232 243 |
| Van Clee e H J | 179 | Ziegenhagen, G | 59 60 64 69 |
| Van Heerd P F | 97 103 | | |

- Caribou, lifespan of, 92-94
 Cat, lifespan of, 134
 lifetime energy expenditure of, 127
 Catfish, lifespan and size of, 154 220, 223
 Cattle, breeding of, 57-58
 lifespan of, 57-65 70-71
 Cell, effect of temperature on, 281
 Centenarians, accuracy of age of, 13
 Central nervous system, control of vital functions by, 128-129
 Centrarchidae, protein metabolism in, 182-183
Cervus elaphus, lifespan of, 92-94
 Char, fecundity of, 191-192
 lifespan and size of, 152
 Characin, lifespan of, 224
 Charadriiformes, mortality rate of, 101
 Chickens, arteriosclerosis in, 110 113
Chirodomys ghruides, lifespan of, 96
 Cholesterol, in aetiology of arteriosclerosis, 110-111 113
 Cholinesterases, age activity of, 247
Chrysops, lifespan of, 105
 Chub, lifespan and size of, 150 221
 Cleoniformes, mortality rate of, 181
 Clupea, lifespan and size of, 150
Clupeus pygmaeus, lifespan of, 97
Clupea harengus, growth of, 156 157 158
Clupea pallasi, fecundity of, 196 197
 Clupeiformes, lifespan of, 220 222
 Clupeoidel, lifespan and growth in, 160-166
 lifespan and size of, 148
 Clupeoids, survival curves of, 143 145
 Coalfish, lifespan and size of, 148
 Coate's knife-fish, 224
 Cockroaches, effect of diet on, 253-254
 lifespan of, 253 254
 Cod, lifespan and growth of, 160-166
 lifespan and size of, 148
 Colubridiformes, mortality rate of, 101
 Cormorants, arteriosclerosis in, 109
Coregonus alpeiformis, survival curves of, 143 144
 Cottoidel, lifespan and size of, 152
Cottus gobio, survival curves of, 143 145
 Cow(s), average age of different breeds, 59
 cause of death, 63-64
 lifespan of, 58-64 70
 lifetime energy expenditure of, 127
 Cowfish, lifespan of, 221
 Creatinuria, in rats, 83
Crisiomeles namaycush, mortality rates of, 145
 Croaking gourami, 224
 Cunner, lifespan of, 221
 Cyprinids, metabolism of, 169
 Cypriniformes, lifespan of, 220 222 224
 Cyprinodontiformes, lifespan and size of, 192 224
 Cypseloidel, lifespan and size of, 152
 Dab, fecundity in, 192 200-202
 Dace, lifespan of, 223
Dasyatis akajel, lifespan and growth of, 163
 Death, accuracy of age at, 12-13
 Death curves, 6-9, 15, 17, 186-296
 of horses, 56
 Death rate, anticipated, 4, 5, 7, 12, 15
 laws governing, 2-4
 senescent, 4, 5, 6, 7, 10, 11, 12
 Deaths, accidental, 17
 Deer, lifespan of, 91-94
 Diet, effect on amyloid, 79
 effect on bees, 254
 effect on cockroach, 253, 254
 effect on fertility, 34
 effect on fish, 178 215-216
 effect on flies, 249-255
 effect on growth, 84-85, 177, 178, 254-255
 effect on lifespan, 169 177 178, 249-255 265-267 268 282
 effect on lifespan of rats, 78 83-85 87 88 251-252, 254
 effect on mice, 79-80
 effect on mosquito, 255
 effect on sexual maturity, 84-85
 effect on trout, 253 254
 effect on wasps, 255
 protein in, 252-254
Dipodomys heermanni, lifespan of, 96
 Disease, onset of and longevity, 72 89
 Doctor fish, lifespan of, 221
 Dog, lifespan of, 134
 lifetime energy expenditure of, 127
 Dog snapper, lifespan of, 221
 Dragonet, lifespan and size of, 152
 mortality rate of, 146
 survival curves of, 143 145
Drosophila subobscura, lifespan of, 262, 266
 rate of ageing in, 269-285
 Drum, lifespan of, 221
 Ducks, arteriosclerosis in, 109
 Dwarf top-minnow, reproduction and senescence in, 189
 Eel, lifespan and size of, 152 223
 natural death in, 174
 Electric catfish, lifespan of, 224
 Electric eel, lifespan of, 224
 Environment, effect on lifespan, 167-168, 229
 effect on onset of disease, 86-87
Epiplatys guttatus, protein metabolism in, 183 184
 Falconiformes, mortality rate of, 101
 Fat body in bees, 233 235, 237 238, 239, 244
 Fat(s), in pollen, 237
 storage in bees, 237, 238, 239
 Fecundity, variation of in fish, 191-192
 Fertility, effect of parental age on, 56
 Finch, lifespan of, 99, 103

SUBJECT INDEX

- Accipitres, arteriosclerosis in 109
 Acipenseriformes, lifespan and size of 152
 220 222
Acipenser fulvescens survival curves of
 143, 144
Acipenser ruthenus oldest age of 191
 Actuarial aspects of human lifespan, 2 20
Aedes aegypti effect of diet on 255
 Age changes due to in fish 218
 effect on fecundity in fish 198 200 201
 effects of in insects, 247 268
 effect on reproduction in fish 181 182
 186-200
 parental and lifespan 21 34
 Ageing genetics of in *Drosophila* 278
 280, 283
 in *Drosophila* 269-285
 molecular changes in 121 131
 physiological changes in fish due to
 181-211
 theory of 129-131 269-272 297 281
 282
 Albatross, lifespan of 100 103
 Albumin, effect on bees 235
 Allometry of lifespan, 125
Alsa sapidissima fecundity of 191 192
 Amniotes, lifespan of 222
 Amino acids, effect on bees, 238
 in pollen 237
 Amyloid, effect of diet 79
 Amyloidosis, in mice 80-81
 Angelfish, lifespan of 221
 protein metabolism in 183 185
 Anglia cattle, lifespan of 60
 Anguilliformes, lifespan of 224
 Anguilloides, lifespan and size of 152
 Animal populations, control of 296-297
 Anseres, arteriosclerosis in 109
 Anseriformes, mortality rate of 101
Apis mellifera 247
 Apodiformes, mortality rate of 101
 Arctic char, lifespan of 147
Ardea cinerea, lifespan of 99
 Argentine, lifespan and size of 150
 Arteriosclerosis, aetiology of 107 108
 brain in, 107
 cholesterol in 110-111 113
 in birds, 106-114
 in fish, 225
 in mammals, 109
 in monkeys, 108
 site of, 110
 Bass, lifespan of, 220, 221, 223
 Batrachoidiformes, lifespan of, 221
 Bats, lifespan of 97 103
 Bees, ageing in 248
 brain cells in 248
 effect of diet, 254
 effect of protein on 254
 in tropics, 246
 lifespan of
 caged 235-239
 factors influencing 231 246
 in free-flying colony 231 235
 physiological condition of
 free-flying 231 235
 caged 235 239
 yearly life cycle in 239-240
 Beryciformes, lifespan of 220
 Birds, arteriosclerosis in 106-114
 lifespan of in captivity 103
 lifespan of in nature 90-105
 Bison, lifespan of 104
 Blackfish lifespan of 221
 Black pied cattle, lifespan of 60
 Biennialoides, lifespan and size of 152
Biennius pholis growth of 156 157 158
 Blenny, growth of 156 157 158
 lifespan and size of 152
 Blue-head lifespan of 221
 Blue striped grunt lifespan of 221
 Body weight, relationship to lifespan, 115
 119
 Bowfin, lifespan of 222
 Brain, in arteriosclerosis 107
 internal environment of 133
 weight of
 relationship with lifespan 115 139
 Brain cells, ageing in 248
 Breast cancer in cattle 71
 Bullhead, effect of diet on 169
 lifespan and size of 152 223
 survival curves of 143 145
 Bulls, causes of death in 65
 lifespan of 64 65
 Burbot lifespan of 221
Buteo buteo lifespan of 99
 Butterfly fish, lifespan of 121
 Buzzards, lifespan of 99
 Callionymoides, lifespan and size of 152
Callionymus lyra mortality rate of 146
 survival curves of 143 145
 Cancer, in fish, 216 226
 Cancer eye in cattle 71
 Capelin, lifespan and size of, 150
 mortality rate of 146
Copeolus copeolus lifespan of, 92-94
 Carbohydrate, in pollen, 237, 238

- Caribou*, lifespan of, 92-94
Cat, lifespan of, 134
 lifetime energy expenditure of, 127
Catfish, lifespan and size of, 154 220, 223
Cattle, breeding of, 57-58
 lifespan of, 57-65 70-71
Celk, effect of temperature on, 281
Centenarians, accuracy of age of, 13
Central nervous system, control of vital functions by, 128-129
Centrarchidae, protein metabolism in, 182 183
Cervus elaphus lifespan of, 92 94
Char, fecundity of, 191-192
 lifespan and size of, 152
Characin, lifespan of, 224
Charadriiformes, mortality rate of, 101
Chickens, arteriosclerosis in, 110 113
Chirodomys glaucoideus lifespan of, 96
Cholesterol, in aetiology of arteriosclerosis, 110-111 113
Cholinesterases, age activity of, 247
Chrysops lifespan of, 105
Chub, lifespan and size of, 140 221
Ciconiiformes, mortality rate of, 101
Cisco, lifespan and size of, 150
Citellus pygmaeus, lifespan of, 97
Clupea harengus growth of, 156 157 158
Clupea pallasii fecundity of, 196-197
Clupeiformes, lifespan of, 220 222
Clupeoides, lifespan and growth in, 160-166
 lifespan and size of, 148
Clopeoids, survival curves of, 143 145
Coalfish, lifespan and size of, 148
Coale's knifefish, 224
Cockroaches, effect of diet on, 253-254
 lifespan of, 253-254
Cod, lifespan and growth of, 160-166
 lifespan and size of, 148
Columbiformes, mortality rate of, 101
Cornuosis, arteriosclerosis in, 109
Corregonus clupeiformis survival curves of, 143 144
Cottoides lifespan and size of, 152
Cottus gobio survival curves of, 143 145
Con(s) average age of different breeds, 59
 cause of death, 63-64
 lifespan of, 58 64 70
 lifetime energy expenditure of, 127
Cowfish, lifespan of, 221
Creatinuria in rats, 83
Cryptomus namata, cash mortality rates of, 145
Croaking gourami, 224
Cunner lifespan of, 221
Cyprinids, metabolism of, 169
Cypriniformes, lifespan of, 220, 222 224
Cyprinodontiformes, lifespan and size of, 152 224
Cyprinoides, lifespan and size of, 152
Dah, fecundity in, 192, 200-202
Dace, lifespan of, 221
Dasyatis akajel, lifespan and growth of, 163
Death, accuracy of age at, 12-13
Death curves, 6-9, 15, 17, 286-296
 of horses, 56
Death rate, anticipated, 4, 5, 7, 12, 15
 laws governing, 2-4
 senescent, 4, 5, 6, 7, 10, 11, 12
Deaths, accidental, 17
Deer, lifespan of, 91-94
Diet, effect on amyloid, 79
 effect on bees, 254
 effect on cockroach, 253, 254
 effect on fertility, 34
 effect on fish, 178, 215-216
 effect on flies, 249-255
 effect on growth, 84-85 177, 178 254-255
 effect on lifespan, 169 177-178, 249-255, 265-267 268 282
 effect on lifespan of rats, 78, 83-85, 87, 88 251-252 254
 effect on mice, 79-80
 effect on mosquito, 255
 effect on sexual maturity, 84-85
 effect on trout, 253 254
 effect on wasps, 255
 protein in, 252-254
Dipodomys heermanni lifespan of, 96
Disease, onset of and longevity, 72-89
Doctor fish, lifespan of, 221
Dog lifespan of, 134
 lifetime energy expenditure of, 127
Dog snapper, lifespan of, 221
Dragonet, lifespan and size of, 152
 mortality rate of, 146
 survival curves of, 143 145
Drosophila subobscura lifespan of, 262, 266
 rate of ageing in, 269-285
Drum, lifespan of, 221
Ducks, arteriosclerosis in, 109
Dwarf top-munnow, reproduction and senescence in, 189
Eel, lifespan and size of, 152, 223
 natural death in, 174
Electric catfish, lifespan of, 224
Electric eel, lifespan of, 224
Environment, effect on lifespan, 167-168, 229
 effect on onset of disease, 86-87
Epinephelus guttatus protein metabolism in, 181 184
Falconiformes, mortality rate of, 101
Fat body in bees, 233, 235, 237 238, 239, 244
Fat(s), in pollen, 237
 storage in bees, 237 238, 239
Fecundity, variation of in fish, 191-192
Fertility, effect of parental age on, 56
Flech, lifespan of, 99, 103

Ide, lifespan of 223
 Index of cephalization, 123, 135
 Infectious disease, in fish, 213-214
 Insects (see also under names of species)
 aging in, 247-268
 lifespan of 105
 overwintering in 232 234 240
 Irradiation, effect on lifespan, 19-20, 138-
 141, 282, 290, 292
 effect on onset of disease, 87, 88

 Jack, lifespan of 220

 Kidney disease, in man and rat, 74-77
 Killifish, lifespan of 220

Labidesthes, growth of 156 157 158
Labidesthes sicculus, mortality rate of,
 346
Lagonostica senegalensis lifespan of 99
Lamprolaima, lifespan of 220
 Laws of mortality, 2 3, 302-311
Lebistes reticulatus effect of diet on, 169
 fecundity in 209
 regeneration in, 208-210
Lepidosteiformes, lifespan of 223, 224
Leucichthys kaysi survival curves of 143
 145
Leucichthys sardinella metabolism of 169
 mortality rates of 145
Leuresthes tenuis survival curves of 143
 Lifespan, allometry of 125
 and parental age, 21-34
 effect of brain and body weight on 115-
 139
 effect of diet on 169 249 255 282
 effect of disease on, 72-89
 effect of egg laying on in *Drosophila*,
 275-278
 effect of environment, 167-168
 effect of growth and size on 147 159
 effect of hibernation 103-104
 effect of metabolism, 103-104 124-126
 129 136-137 169-170
 effect of mitotic inhibitors, 136
 effect of parental age 43-47 53 259-
 262
 effect of radiation on 19-20 138-141,
 282, 290 292
 effect of reproduction 179 275-279
 284-285
 effect of temperature on in *Drosophila*
 273 279 283 284
 effect of thyroid gland on 137
 genetic aspects of 33 53 137
 in nineteenth century 23 32
 mathematical basis of 286-296
 measurement of 133-134 138-141
 methods of study 21 26
 of albatross, 100 103
 of Arabian horses, 42
 of *Ardea cinerea* 99
 of bats, 103
 of bears, factors influencing, 231-246

Lifespan
 of bison, 105
 of birds in captivity, 103
 of birds in Nature, 90-105
 of bulls, 64-65
 of *Buteo buteo* 99
 of buzzards, 99
 of *Capreolus capreolus*, 92-94
 of caribou, 92 94
 of cat, 134
 of cattle, 57-65, 70-71
 of *Cervus elaphus*, 92-94
 of *Chirodomys gliroides*, 96
 of *Citellus pygmaeus*, 97
 of cockroaches, 253-254
 of deer 91 94
 of *Dipodomys heermanni* 96
 of dog, 134
 of *Drosophila subobscura*, 262, 266
 of English thoroughbred horses, 35-56
 of fish 99, 103
 of fish characteristics of long, 217-218
 of fish in captivity 212-230
 of fish in Nature, 142-180
 of fish of different species, 219-224
 of flies, 105, 249-262, 287-288
 of Hadding mares, 43
 of herons, 99
 of Hokkaido ponies, 43
 of horses, 35-56 65-69
 of houseflies 249-262, 287-288
 sex differences in 255-259
 of human beings actuarial aspects of,
 2-20
 of humming birds 104
 of insects, 105
 of kangaroo rats, 96
 of *Lagonostica senegalensis*, 99
 of Lipitza horses 43
 of mammals in Nature, 90-105
 of man and woman compared, 10-11,
 16
 of *Megadyptes antipodes*, 100
 of mosquitoes, 105
 of mouse 95-96 287
 of *Myotis mystacinus* 97
 of *Odontocercus hemionus*, 92-94
 of *Oris dalli* 92-94
 of owls 99
 of parent and progeny correlated, 47-
 49
 of *Parus major*, 100
 of *Passer domesticus* 99
 of Passerines, 99 100
 of *Peromyscus leucopus*, 95-96
 of rabbits 97
 of *Rangifer arcticus* 92 94
 of rats, 95-96, 251-252
 effect of diet 78
 effect of disease 72-89
 of sheep, 91-94
 of shrews, 97
 of skylark, 97
 of *Sorex araneus* 97

Fish (see also under common names)

- changes in due to ageing, 218
- effect of diet on, 167
- effect of fat diet on, 215-216
- effect of growth and size on lifespan 147-159
- effect of toxic substances on, 177
- egg counting in, 192-193
- fecundity in relation to age in, 186-206
- growth and senescence in, 217
- growth of,
 - utilization of protein in 182-186
- growth rate and lifespan 227 229
- infectious disease in 213-214 228
- lifespan of
 - characteristics of long, 217 218
 - in different species, 219-224
 - in captivity 212-230
 - in Nature 142-180
- lipid metabolism in 227
- metabolic disease in 216
- metabolism of 169-170
- natural death and reproduction in 170-174
- natural mortality of 142 147
- neoplasia in 216
- nutrition in 215
- ovaries of 193
- parasites in 213 216
- physiological changes due to ageing 181 211
- protein utilization in 210
- relationship of age mortality and growth in 160-166
- survival curves of 143 147
- variation in fecundity of 191 192
- Flamingoes, effect of diet on 112
- Flounder, lifespan and size of 150
- Fly (see Housefly)
- Food, conversion of in fish 186
- Gadiformes, lifespan of 223
 - lifespan and growth of 160-166
 - lifespan and size of 148
 - metabolism of 169
- Gall, arteriosclerosis in 109
- Galiformes, mortality rate of 101
- Gambusia a. affinis reproduction and senescence in 187 189
- Gannets, arteriosclerosis in 109
- Gar, lifespan of 222
- Gasterosteiformes, lifespan of 152 223
- Gasterosteus aculeatus effect of environment of 168
- Gerse, arteriosclerosis in 109
- Genetics, and lifespan 137
 - of ageing, in *Drosophila* 278 280 283
- Glomerulonephritis, in man 77
- in rats, 74-76
- Glycogen, storage in bees, 237 238 239
- Golden Shiner, 223
- Goldfish, lifespan of 223
 - metabolism of, 170

- Gompertz' Law, 2, 72, 302
- Gompertz-Makham equations, 117
- Grayling, effect of environment of, 168
- Grouper, lifespan of, 220
- Growth, 296, 298
 - effect of diet, 84-85, 254-255
 - effect on lifespan, 147-159, 160-166
- Grunion, lifespan and size of, 154
- Guinea pig, lifetime energy expenditure of, 127
- Guppies, effect of diet on 169
 - growth of, 229 230
 - regeneration in 208-210
 - reproduction in, 171, 209

- Habrobracon juglandis*, 255
- Haddock, effect of age on fecundity, 198-200
 - lifespan and size of 148
 - relationship of fecundity and body weight 200
 - sex organs in 190
- Hake, lifespan and size of 148
- Halibut, lifespan and size of 148, 150
- Heart disease in man and rat, 74-77
- Heron, lifespan of 99
- Herring fecundity of 196-197
 - growth of 156, 157 158
 - lifespan and growth of 160-166
 - lifespan and size of 148
 - relationship of gonad growth to body weight 193
 - relation of size and maturity 172
 - survival curves of 143 145
- Hesperoleu us venustus* effect of environment on 164
- Heterandria formosa* reproduction and senescence in 189
- Hibernation, effect on lifespan 103-104
- Highland cattle lifespan of 59 61 62
- Hippocampus hudsonius* lifespan of 147
- Hippoglossoides platessoides* fecundity in, 192
- Hippoglossus* spp. lifespan of 147
- Holocanthus bermudensis* protein metabolism in 181 185
- Horses, breeding of 53
 - causes of death in 68
 - coat colour and longevity 49 50
 - death curves of 56
 - lifespan of under various climatic conditions 65 69
 - lifespan of English thoroughbred 35 46
 - lifetime energy expenditure of 127
 - survival curves of 35-42
- Housefly ageing in 247 262
 - effect of diet on 249-253
 - lifespan of 249 262, 287 288
 - effect of paternal age 259-262
 - sex differences in, 255-259
 - sex ratio in 249
- Humming birds, lifespan of, 105

- Pharyngeal glands, in bees, 233 235 237
238 239 244
- Physiological function, stability of 135
- Pike, lifespan of 222
- Ple-kullie lifespan of 224
- Pilotfish, lifespan of 221
- Plalce, fecundity of 202 206
growth of 157 158 159
lifespan and size of 150
mortality rates of 167
reproduction and growth in, 189-190
- Pleuronectes platessa*, fecundity in, 202
206
growth of 157 158
reproduction and growth in, 189-190
- Pleuronectoidea, lifespan and growth of
161 166
lifespan and size of 148
- Poculidae, reproduction and age n, 181
186-189
- Pollen, contents of 237
effect on bees 236-240
- Pompano, lifespan of 220
- Porcupine fish, lifespan of 221
- Porgy lifespan of 221
- Poultry arteriosclerosis in 110, 113
- Procellariiformes mortality rate of 101
- Protein, effect on bees 234 254
effect on *Drosophila*, 266-267
nd et 252 254
in pollen, 237 238
sto age n bees, 237 238, 239
utilization of n fish 210
- Prorhynchus* arteriosclerosis n 108-109 110
- Padding wale, lifespan of 221
- Puffer lifespan of 221
- Pygospio* growth of 156 157
158
- Quillback, lifespan of 222
- Rabbit, contents of lifespan of 97
- Rajiformes, lifespan and size of 154 220
- Rangferia lifespan of 92 94
- Rasbora, lifespan of 224
- Rata, brown lifespan of 95-96
causes of death of 82-83
disease n effect on lifespan 72-89
effect of diet on 78 251 252 254 265
268
kanga on lifespan of 96
lifespan of 95 96 251 252
lung disease n 82
nephrosis n 83
- Ru us d ius lifespan of 95-96
- Ray lifespan and size of 154 163 221
- Red hind, lifespan of 240
p o c n metabolism n, 183-185
- Regeneration, n guppies, 208-210
- Reproduction, effects of age on in fish,
181 182 186-186
effect on lifespan 179 275-279 284-
285
in fish, 10-174
- Roach, lifespan of 222
- Rockfish, lifespan of 220
- Rosy tetra, lifespan of 224
- Rubner's theory of ageing, 125-126 128
- Rodder fish, lifespan of, 221
- Sailfish, lifespan and size of 154
- Salivary glands, in bees, 233 235 237 238
239
- Salmo gairdneri* growth rates of 182
- Salmon, fecundity of 192, 197 198
growth of 156, 157 158
lifespan of 222
lifespan and growth of 160-166
lifespan and size of 150 252
mortality rates of 145 166
natural death n, 174
relation of size and maturity 172
reproduction in, 179
- Salmonoides, lifespan and growth of 161
166
lifespan and size of 150
- Salmo salar* fecundity in, 197 198
- Salvelinus alpinus* lifespan of 147
- Sand dab, lifespan and size of 148
- Sardina pilchardus* effect of environment
on 168
- Sardines, effect of environment on, 168
- Sauger lifespan and size of 154
- Scandinavian lifespan of 21 26
- Scat, lifespan of 221
- Scombroidea, lifespan and size of 154
- Sea horse lifespan of, 147 154
- Senile death, in fish, 189
- Sex differences, in growth of fish 159
in mortality among fish, 145 166-167
n reactions to environment in fish,
178
- Sex organs, changes n due to age in fish,
218
in fish 229
relationship to body weight in fish,
193-196
- Sexual maturity effect of diet, 84-85
n fish 170-171
- Shad, fecundity of 191 192
- Shark, lifespan of 220
- Sheep lifespan of 91 94
- Sheepshead, lifespan of 221
- Shrews, lifespan of 97
- Siluridae, lifespan and size of 154
- Size, effect on lifespan, 147 159
- Slipjack, metabolism of 170
- Smelt, lifespan of 147 150
- Snake-head, lifespan of 224
- Snapper lifespan of 221
- Sole, lifespan and size of 150
- Sorex araneus* lifespan of, 97
- Southern lifespan of 97
- Soya flour effect on bees, 235
- Spadefish, lifespan of 221
- Sparrows, lifespan of 99
- Sphenisciformes, mortality rate of 101
- Sprat, lifespan and size of 148

Lifespan

- of sparrows, 99
- of *Sterna hirundo*, 97-99
- of *Sirix aluco*, 99
- of swifts, 100, 103 104
- of terns, 97-99, 104
- of tits, 100
- of trout, 265
- of ungulates, 91-95
- relationship to index of cephalization, 123-125
- relationship with growth, 160-166
- Life tables, 9-11
 - limitations of 11-12, 18
- Liver, in fish, 215-216, 227
- Longevity (see also Lifespan)
 - onset of disease and 72 89
- Look-down, lifespan of 221
- Lovettia seall, mortality rate of 146
- Lung disease, in rats, 82
- Lungfish, lifespan of, 224
- Mackerel, lifespan and size of 154
- Makeham's Law, 2 302
- Malayan flying barb, lifespan of 224
- Mallotus villosus mortality rate of 146
- Mammals, arteriosclerosis in 109
 - lifespan of in nature 90-105
 - life tables of 117 118
 - relationship of brain and body weight to lifespan 115 139
- Man, disease in effect on lifespan 72 89
 - lifetime energy expenditure of, 127
- Mandibular glands, in bees, 233
- Maternal age, effect on lifespan 23-27 31 32
- Megal worms, effect of paternal age on lifespan 262
- Megadryptes antipodis lifespan of 100
- Melanogrammus aeglefinus fecundity of 198-200
 - sex organs in 190
- Metabolic disease, in fish 216
- Metabolism, effect on lifespan 101 104
 - 124-126 129 136 137 169 170
- Mice, amyloidosis in 80-81
 - effect of diet on 74 80
 - lifespan of 287
 - white footed lifespan of 95 96
- Miller's thumb, lifespan of 223
- Minerals, in pollen 237
- Milano, lifespan and size of 152
- Mitotic inhibitors, 136
- Molecular changes in ageing, 129 131
- Monk eye, arteriosclerosis in 108
- Moonfish, lifespan of 221
- Mortality, relation with age and growth 160-166
 - theory of 127 129
- Mortality rates, 286 296
 - laws governing, 2 5
 - mathematical models for, 302 311
 - sex differences in, 81
- Mosquito, effect of diet on, 255
 - lifespan of, 105
- Mosquito fish, mortality rates of, 167
 - reproduction and senescence in, 187-189
- Mothers, age of, effect on lifespan, 23-27, 31, 32
- Mugiloides, lifespan and size of, 154
- Musca domestica (see Housefly)
- Muscular degeneration, 77
 - in rats, 74-76
- Muskallunge, lifespan of 222
- Myocardial degeneration, 77
 - in rats, 74-76
- Myotis mystacinus, lifespan of, 97
- Neoplasia, in fish 216 226
- Neothunnus macropus fecundity of, 193
- Nephrosis, in man 77
 - in rats 74-76 83
- Nerve cells, in bees, 234 244
- Nitrogen, in pollen 236
- Odocoileus hemionus lifespan of 92-94
- Oncorhynchus nerka fecundity in, 197-198
 - growth of 156 157 158
- Oncorhynchus spp. mortality rates of 145
- Ophiocephaliformes, lifespan of 224
- Orange chromide, lifespan of 224
- Ovaries, effect of age on in fish 201
 - growth of in herring 195
 - in bees 233 235 237 238 239 243
 - of Drosophila 275 277 285
 - in fish 193
 - changes due to age 182
- Overwintering, 232 234 240
- Ovis aries lifespan of 92 94
- Ovis, lifespan of 99
- Palometa, lifespan of 220
- Parasites, in fish 213 216 228
- Parental age, effect on fertility of offspring 46
 - effect on lifespan 21 34 41 47 51 249 262
- Parental death, in fish 189
- Parrots, arteriosclerosis in 109 110
- Parus major lifespan of 100
- Passer domesticus lifespan of 99
- Passeres, arteriosclerosis in 109
- Passerines, lifespan of 99 100
- Pelecaniformes, mortality rate of 101
- Pelicans, arteriosclerosis in 109
- Penguin, mortality rate of 100
- Perna fluviatilis survival curves of 141 144
- Perch, effect of diet 178
 - lifespan and size of 154 220 223
 - survival curves of 143 144 145
- Perciformes, lifespan of 220 223 224
- Percoides, lifespan and size of 154
- Peromyscus leucopus, lifespan of, 93 96

- Pharyngeal glands, in bees, 233, 235, 237, 238, 239, 244
- Physiological function, stability of, 135
- Pike, lifespan of, 221
- Pike-killie, lifespan of, 224
- Pilotfish, lifespan of, 221
- Plaice, fecundity of, 202-206
growth of, 157, 158, 159
lifespan and size of, 150
mortality rates of, 167
reproduction and growth in, 189-190
- Pleuronectes platessa*, fecundity in, 202-206
growth of, 157, 158
reproduction and growth in, 189-190
- Pleuronectes*, lifespan and growth of, 161-166
lifespan and size of, 148
- Procellariidae, reproduction and age in, 181, 186-189
- Pollen, content of, 237
effect on bees, 236-240
- Pompano, lifespan of, 220
- Porcupine fish, lifespan of, 221
- Porxy, lifespan of, 221
- Poultry, arteriosclerosis in, 110, 113
- Procellariiformes, mortality rate of, 101
- Protein, effect on bees, 234, 254
effect on *Drosophila*, 266-267
in diet, 232, 254
in pollen, 237, 238
storage in bees, 237, 238, 239
utilization of in fish, 210
- Psittaci, arteriosclerosis in, 108-109, 110
- Padding wife, lifespan of, 221
- Puffer, lifespan of, 221
- Pycopterus pangloss*, growth of, 156, 157, 158
- Quillback, lifespan of, 222
- Rabbits, cottontail, lifespan of, 97
- Rajiformes, lifespan and size of, 154, 220
- Rangifer arcticus*, lifespan of, 92-94
- Rashora, lifespan of, 224
- Rats, brown, lifespan of, 95-96
causes of death of, 82-83
disease in, effect on lifespan, 72-89
effect of diet on, 78, 251, 252, 254, 265, 268
kangaroo, lifespan of, 96
lifespan of, 95, 96, 251, 252
lung disease in, 82
nephrosis in, 83
- Rattus rattus*, lifespan of, 95-96
- Ray, lifespan and size of, 154, 163, 221
- Red blind, lifespan of, 220
protein metabolism in, 183-185
regeneration, in puppies, 208-210
Reproduction, effects of age on in fish, 181, 182, 186-206
effect on lifespan, 179, 275-279, 284-285
in fish, 170-174
- Rough, lifespan of, 212
- Rockfish, lifespan of, 220
- Rosy tetra, lifespan of, 224
- Rubber's theory of ageing, 125-126, 128
- Rudder fish, lifespan of, 221
- Sailfish, lifespan and size of, 154
- Salivary glands, in bees, 233, 235, 237, 238, 239
- Salmo gairdneri*, growth rates of, 182
- Salmon, fecundity of, 192, 197-198
growth of, 156, 157, 158
lifespan of, 222
lifespan and growth of, 160-166
lifespan and size of, 150, 152
mortality rates of, 145, 166
natural death in, 174
relation of size and maturity, 172
reproduction in, 179
- Salmonidae, lifespan and growth of, 161-166
lifespan and size of, 150
- Salmo salar*, fecundity in, 197-198
- Salvelinus alpinus*, lifespan of, 147
- Sand dab, lifespan and size of, 148
- Sardina pilchardus*, effect of environment on, 168
- Sardines, effect of environment on, 168
- Sauger, lifespan and size of, 154
- Scandinarvians, lifespan of, 21-26
- Scat, lifespan of, 221
- Scombridae, lifespan and size of, 154
- Sea horse, lifespan of, 147, 154
- "Senile" death, in fish, 189
- Sex differences, in growth of fish, 159
in mortality among fish, 145, 166-167
in reactions to environment in fish, 178
- Sex organs, changes in due to age in fish, 218
in fish, 229
relationship to body weight in fish, 193-196
- Sexual maturity, effect of diet, 84-85
in fish, 170-171
- Shad, fecundity of, 191-192
- Shark, lifespan of, 220
- Sheep, lifespan of, 91, 94
- Sheephead, lifespan of, 221
- Shrews, lifespan of, 97
- Siluridae, lifespan and size of, 134
- Size, effect on lifespan, 147-159
- Slapjack, metabolism of, 170
- Smelt, lifespan of, 147, 150
- Snake-head, lifespan of, 224
- Snapper, lifespan of, 221
- Sole, lifespan and size of, 150
- Sorex araneus*, lifespan of, 97
- Souslik, lifespan of, 97
- Soya flour, effect on bees, 235
- Spadefish, lifespan of, 221
- Sparrows, lifespan of, 99
- Spherisciformes, mortality rate of, 101
- Sprat, lifespan and size of, 143

Lifespan

- of sparrows, 99
- of *Sterna hirundo*, 97-99
- of *Strix aluco*, 99
- of swifts, 100, 103, 104
- of terns, 97-99, 104
- of tits, 100
- of trout, 265
- of ungulates, 91, 95
- relationship to index of cephalization, 123-125
- relationship with growth, 160-166
- Life tables, 9-11
 - limitations of, 11, 12, 18
- Liver, in fish, 215-216, 227
- Longevity (see also Lifespan)
 - onset of disease and, 72, 89
- Look-down, lifespan of, 221
- Loxia scotti* mortality rate of, 146
- Lung disease, in rats, 82
- Lungfish, lifespan of, 224
- Mackeral, lifespan and size of, 154
- Makeham's Law, 2, 302
- Malayan flying barb, lifespan of, 224
- Mallothus villosus* mortality rate of, 146
- Mammals, arteriosclerosis in, 109
 - lifespan of in Nature, 90-105
 - life tables of, 117, 118
 - relationship of brain and body weight to lifespan, 115, 139
- Mean, disease in, effect on lifespan, 72, 89
 - lifetime energy expenditure of, 127
- Mandibular glands, in bees, 233
- Maternal age, effect on lifespan, 21, 27, 31, 32
- Meal worm, effect of paternal age on lifespan, 262
- Megadryptes antipodes* lifespan of, 100
- Melanogrammus aeglefinus* fecundity of, 198, 200
 - sex organs in, 190
- Metabolic disease in fish, 216
- Metabolism, effect on lifespan, 103, 104, 124-126, 129, 136, 137, 169, 170
- Mice, amyloidosis in, 80, 81
 - effect of diet on, 79, 80
 - lifespan of, 287
 - white-footed lifespan of, 95, 96
- Miller's thumb, lifespan of, 221
- Minerals, in pollen, 237
- Minkow, lifespan and size of, 152
- Mitotic inhibitors, 116
- Molecular changes in ageing, 129, 131
- Monkeys, arteriosclerosis in, 108
- Moonfish, lifespan of, 221
- Mortality, relation with age and growth, 160-166
 - theory of, 127, 129
- Mortality rates, 266-296
 - laws governing, 2, 5
 - mathematical models for, 302, 311
 - sex differences in, 81

- Mosquito, effect of diet on, 255
 - lifespan of, 105
- Mosquito fish, mortality rates of, 167
 - reproduction and senescence in, 187-189
- Mothers, age of, effect on lifespan, 23-27, 31, 32
- Mugiloidae, lifespan and size of, 154
- Musca domestica* (see Housefly)
- Muscular degeneration, 77
 - in rats, 74-76
- Muskallunge, lifespan of, 222
- Myocardial degeneration, 77
 - in rats, 74-76
- Myotis mystacinus* lifespan of, 97
- Neoplasia in fish, 216, 226
- Neothunnus macropterus* fecundity of, 193
- Nephrosis, in man, 77
 - in rats, 74-76, 83
- Nerve cells, in bees, 244, 244
- Nitrogen, in pollen, 236
- Odocoileus hemionus* lifespan of, 92, 94
- Oncorhynchus nerka* fecundity in, 197-198
 - growth of, 156, 157, 158
- Oncorhynchus* spp. mortality rates of, 145
- Ophioccephaliformes, lifespan of, 224
- Orange chromide, lifespan of, 224
- Ovaries, effect of age on in fish, 201
 - growth of in herring, 195
 - in bees, 233, 235, 237, 238, 239, 243
 - of *Drosophila*, 275, 277, 285
 - in fish, 193
 - changes due to age, 182
- Overwintering, 232, 234, 240
- Oryzias latipes* lifespan of, 92, 94
- Owls, lifespan of, 99
- Palometa, lifespan of, 220
- Parasites, in fish, 213, 216, 228
- Parental age, effect on fertility of offspring, 56
 - effect on lifespan, 21, 14, 41, 47, 53, 259, 262
- Parental death, in fish, 189
- Parrots, arteriosclerosis in, 109, 110
- Parus major* lifespan of, 100
- Passer domesticus* lifespan of, 99
- Passeris*, arteriosclerosis in, 109
- Passerinus*, lifespan of, 99, 100
- Pelecaniformes, mortality rate of, 101
- Pelicans, arteriosclerosis in, 109
- Penguin, mortality rate of, 100
- Per a tumulus* survival curves of, 143, 144
- Perch, effect of diet, 178
 - lifespan and size of, 154, 220, 223
 - survival curves of, 143, 144, 145
- Perciformes, lifespan of, 220, 223, 224
- Percoidae, lifespan and size of, 154
- Peromyscus leucopus* lifespan of, 95-96

- Pharyngeal glands, in bees, 233 235 237
238 239 244
- Physiological function, stability of 135
- Pike, lifespan of 222
- Pike-billie, lifespan of 224
- Pilotfish, lifespan of 221
- Plaice, fecundity of 202 206
growth of 157 158 159
lifespan and size of 150
mortality rates of 167
reproduction and growth in 189-190
- Pleuronectes platessa* fecundity in 202
206
growth of 157 158
reproduction and growth in, 189-190
- Pleuronectoides*, lifespan and growth of
161 166
lifespan and size of 148
- Podilidae reproduction and age in 181
186-189
- Pollen, content of 237
effect on bees 236-240
- Pompano, lifespan of 220
- Porcupine fish, lifespan of 221
- Porry, lifespan of 221
- Poultry arteriosclerosis in 110 113
- Procellariiformes, mortality rate of 101
- Protein, effect on bees, 234, 234
effect on *Drosophila*, 266-267
in diet 252 254
in pollen, 237 238
storage in bees, 237 238 239
utilization of in fish 210
- Psittacus* arteriosclerosis in 108-109 110
- Puddingwife, lifespan of 221
- Puffer, lifespan of 221
- Pygostolus jugulosus* growth of 156 157
158
- Quillback, lifespan of 222
- Rabbits, cotton-tail lifespan of 97
- Rajiformes, lifespan and size of 154, 220
- Rangifer arcticus* lifespan of 92-94
- Rayback, lifespan of 224
- Rats, brown, lifespan of 95-96
causes of death of 82-83
disease in effect on lifespan 72-89
effect of diet on, 78 251 252, 254 265
68
kangaroo lifespan of 96
lifespan of 95-96 251 252
lung disease in 82
nephrosis in 83
- Rattus* *usur* lifespan of 95-96
- Ray, lifespan and size of 154 163 221
- Red hind, lifespan of 220
protein metabolism in, 183-185
- Regeneration, in guppies 208-210
- Reproduction, effects of age on in fish,
161 182, 186-206
effect on lifespan, 179 275-279 284-
295
in fish, 170-174
- Roach, lifespan of 222
- Rockfish, lifespan of 220
- Rosy tetra, lifespan of 224
- Rubner's theory of ageing, 125-126 128
- Rudder fish, lifespan of 221
- Sailfish, lifespan and size of 154
- Salivary glands, in bees, 233 235 237, 238
239
- Salmo gairdneri* growth rates of 182
- Salmon, fecundity of 192 197 198
growth of 156 157 158
lifespan of 222
lifespan and growth of, 160-166
lifespan and size of 150 152
mortality rates of 145 166
natural death in 174
relation of size and maturity 172
reproduction in 179
- Salmonoides lifespan and growth of 161-
166
lifespan and size of 150
- Salmo salar* fecundity in 197 198
- Salvelinus alpinus*, lifespan of, 147
- Sand eel, lifespan and size of 148
- Sardina pilchardus* effect of environment
on, 168
- Sardines, effect of environment on, 168
- Sauger lifespan and size of 154
- Scandianians, lifespan of, 21 26
- Seal lifespan of 221
- Scombroidei lifespan and size of 154
- Sea horse, lifespan of 147, 154
- Sensile death, in fish 189
- Sex differences, in growth of fish, 159
in mortality among fish, 145 166-167
in reactions to environment in fish,
178
- Sex organs, changes in due to age in fish,
218
in fish 229
relationship to body weight in fish,
193-196
- Sexual maturity effect of diet, 84-85
in fish 170-171
- Shad fecundity of 191 192
- Shark lifespan of 220
- Sheep lifespan of 91 94
- Sheephead lifespan of 221
- Shrews, lifespan of 97
- Siluridae, lifespan and size of 154
- Size effect on lifespan 147 159
- Skipjack, metabolism of 570
- Smelt, lifespan of 147 150
- Snake-head, lifespan of 224
- Snapper lifespan of 221
- Sole lifespan and size of 150
- Sorex araneus* lifespan of 97
- Southern, lifespan of 97
- Soya flour, effect on bees, 235
- Spadefish, lifespan of 221
- Sparrows, lifespan of 99
- Sphenisciformes, mortality rate of 101
- Sprat, lifespan and size of 148

Lifespan

- of sparrows 99
- of *Sterna hirundo* 97-99
- of *Strix aluco* 99
- of swifts, 100 103 104
- of terns 97-99, 104
- of tits, 100
- of trout, 265
- of ungulates 91 95
- relationship to index of cephalization 123-125
- relationship with growth 160-166
- Life tables, 9-11
 - limitations of 11 12 18
- Liver, in fish 215-216 227
- Longevity (see also Lifespan)
 - onset of disease and 72 89
- Look-down, lifespan of 221
- Lovettia scali* mortality rate of 146
- Lung disease, in rats, 82
- Lungfish, lifespan of, 224
- Mackerel, lifespan and size of 154
- Makeham's Law, 2 302
- Malayan flying barb, lifespan of 224
- Mallotus villosus* mortality rate of 146
- Mammals, arteriosclerosis in 109
 - lifespan of in Nature 90-105
 - life tables of 117 118
 - relationship of brain and body weight to lifespan 115-139
- Man, disease in effect on lifespan 72 89
 - lifetime energy expenditure of 127
- Mandibular glands, in bees, 233
- Maternal age, effect on lifespan 23 27 31 32
- Meal worm effect of paternal age on life span, 262
- Megadryptes antipodes* lifespan of 100
- Melanogrammus aeglefinus* fecundity of 198 200
 - sex organs in 190
- Metabolic disease, in fish 216
- Metabolism effect on lifespan 103 104 124-126 129 136 137 169 170
- Mice, amyloidosis in 80 81
 - effect of diet on, 79 80
 - lifespan of 287
 - white footed lifespan of 95 96
- Miller's thumb, lifespan of 223
- Minerals, in pollen 237
- Milano, lifespan and size of 152
- Mitotic inhibitors, 136
- Molecular changes in aging, 129 131
- Monkeys, arteriosclerosis in 108
- Moonfish, lifespan of 221
- Mortality, relation with age and growth 160-166
 - theory of 127 129
- Mortality rates, 286-296
 - laws governing, 2 5
 - mathematical models for, 302 311
 - sex differences in, 81

- Mosquito, effect of diet on, 255
 - lifespan of, 105
- Mosquito fish, mortality rates of, 167
 - reproduction and senescence in, 187-189
- Mothers, age of effect on lifespan, 23-27, 31 32
- Mugiloides, lifespan and size of 154
- Musca domestica* (see Housefly)
- Muscular degeneration, 77
 - in rats 74-76
- Muskallunge, lifespan of 222
- Myocardial degeneration, 77
 - in rats, 74-76
- Myotis mystacinus* lifespan of 97
- Neoplasia* in fish 216 226
- Neothunnus macropus* fecundity of 191
- Nephrosis in man 77
 - in rats 74-76 83
- Nerve cells, in bees 234 244
- Nitrogen, in pollen 236
- Odocoileus hemionus* lifespan of 92 94
- Oncorhynchus nerka* fecundity in 197 198
 - growth of 156 157 158
- Oncorhynchus* spp mortality rates of 145
- Ophiocephaliformes*, lifespan of 224
- Orange chromide, lifespan of 224
- Ovaries effect of age on in fish 201
 - growth of in herring 195
 - in bees 233 235 237 238 239 243
 - of *Drosophila* 275 277 285
 - in fish 193
 - changes due to age 182
- Overwintering 232 234 240
- O. u. doli* lifespan of 92 94
- Owls, lifespan of 99
- Palometa, lifespan of 220
- Parasites, in fish 213 216 228
- Parental age effect on fertility of offspring 36
 - effect on lifespan 21 34 43 47 53 239 262
- Parental death, in fish 189
- Parrots, arteriosclerosis in 109 110
- Parus major* lifespan of 100
- Passer domesticus* lifespan of 99
- Passer*, arteriosclerosis in 109
- Passerines*, lifespan of 99 100
- Pelecaniformes, mortality rate of 101
- Pelicans, arteriosclerosis in 109
- Penguin, mortality rate of 100
- Percia fluviatilis* survival curves of, 143, 144
- Perch, effect of diet 178
 - lifespan and size of 154 220 223
 - survival curves of 143 144 145
- Perciformes, lifespan of, 220 223 224
- Percoides, lifespan and size of, 154
- Peromyscus leucopus*, lifespan of, 95 96

- Pharyngeal glands, in bees, 233 235 237
238, 239 244
- Physiological function, stability of 135
- Pike, lifespan of 222
- Pike-külle lifespan of 224
- Pilotfish, lifespan of 221
- Plaice, fecundity of 202 206
growth of 157 158 159
lifespan and size of 150
mortality rates of 167
reproduction and growth in 189-190
- Pleuronectes platessa*, fecundity in, 202 206
growth of 157 158
reproduction and growth in, 189-190
- Pleuronectoides*, lifespan and growth of 161 166
lifespan and size of 148
- Poeciliidae, reproduction and age in, 181 186-189
- Pollen, content of 237
effect on bees, 236-240
- Pompano, lifespan of 220
- Porcupine fish, lifespan of 221
- Porgy lifespan of 221
- Poultry arteriosclerosis in 110, 113
- Procellariiformes, mortality rate of 101
- Protein, effect on bees, 234 254
effect on *Drosophila*, 266-267
in diet, 252 254
in pollen, 237 238
storage in bees, 237 238 239
utilization of a fish 210
- Psittacus* arteriosclerosis in 108-109 110
- Pudding wife, lifespan of 221
- Puffer lifespan of 221
- Pygoscelis* growth of 156 157 158
- Quailback lifespan of 222
- Rabbits, content of lifespan of 97
- Rapiformes, lifespan and size of 154 220
- Rangifer arcticus* lifespan of 97 94
- Rasbora lifespan of 224
- Rats, brown lifespan of 95-96
causes of death of 82-83
disease in effect on lifespan 72-89
effect of diet on 78 251 252 254 65 268
kangaroo lifespan of 96
lifespan of 95-96 251 252
lung disease in 82
nephrosis in 83
- Rattus* lifespan of 95-96
- Ray lifespan and size of 154 163 221
- Red hound, lifespan of 220
protein metabolism in, 181-185
- Regeneration in pupae, 208-210
- Reproduction, effects of age on in fish, 181 182, 186-206
effect on lifespan, 179 275-279 284-285
in fish, 170-174
- Roach, lifespan of 222
- Rockfish, lifespan of 220
- Rosy tetra lifespan of 224
- Rubber's theory of aging, 125-126 128
- Rudder fish, lifespan of 221
- Sailfish, lifespan and size of 154
- Salivary glands, in bees, 233 235 237 238 239
- Salmo gairdneri* growth rates of 182
- Salmon, fecundity of 192, 197 198
growth of 156, 157 158
lifespan of 222
lifespan and growth of 160-166
lifespan and size of 150 152
mortality rates of 145 166
natural death in 174
relation of size and maturity 172
reproduction in 179
- Salmonoides, lifespan and growth of 161 166
lifespan and size of 150
- Salmo salar* fecundity in, 197 198
- Salvelinus alpinus* lifespan of 147
- Sand dab, lifespan and size of 148
- Sardina pilchardus* effect of environment on, 168
- Sardines, effect of environment on, 168
- Sanger lifespan and size of 154
- Scand navians, lifespan of 21 26
- Scat, lifespan of 221
- Scombroidei lifespan and size of 154
- Sea horse, lifespan of 147 154
- Senile death, in fish, 189
- Sex differences, in growth of fish, 159
in mortality among fish, 145 166-167
in reactions to environment in fish, 178
- Sex organs, changes in due to age in fish, 218
in fish, 229
relationship to body weight in fish, 193-196
- Sexual maturity effect of diet, 84-85
in fish 170-171
- Shad, fecundity of 191 192
- Shark, lifespan of 220
- Sheep lifespan of 91 94
- Sheepshead, lifespan of 221
- Shrews, lifespan of 97
- Siluridae, lifespan and size of 154
- Size, effect on lifespan, 147 159
- Skupjack, metabolism of 170
- Smelt, lifespan of 147 150
- Snake-head, lifespan of 224
- Snapper lifespan of 221
- Soie lifespan and size of 150
- Sorex araneus* lifespan of 97
- Soosuk, lifespan of 97
- Soya flour effect on bees, 235
- Spadefish, lifespan of 222
- Sparrows, lifespan of 99
- Sphenisciformes, mortality rate of 101
- Sprat, lifespan and size of 148

- Lifespan**
 of sparrows, 99
 of *Sterna hirundo*, 97-99
 of *Strix aluco*, 99
 of swifts, 100, 103 104
 of terns 97-99, 104
 of tits, 100
 of trout, 265
 of ungulates, 91-95
 relationship to index of cephalization, 123-125
 relationship with growth 160-166
- Life tables**, 9-11
 limitations of 11-12 18
- Liver**, in fish, 215-216 227
- Longevity** (see also Lifespan)
 onset of disease and 72 89
- Look-down**, lifespan of 221
- Lovettia seali** mortality rate of 146
- Lung disease**, in rats, 82
- Langfish**, lifespan of 224
- Mackerel**, lifespan and size of 154
- Makeham's Law**, 2 302
- Malayan flying barb**, lifespan of 224
- Mallopus villosus** mortality rate of 146
- Mammals**, arteriosclerosis in 109
 lifespan of in Nature 90-105
 life tables of 117 118
 relationship of brain and body weight to lifespan 115 139
- Man**, disease in effect on lifespan 72 89
 lifetime energy expenditure of 127
- Mandibular glands**, in bees 233
- Maternal age**, effect on lifespan 23 27 31 32
- Meal worm** effect of paternal age on life span 262
- Megadiplos antipodes** lifespan of 100
- Melanogrammus aeglefinus** fecundity of 198 200
 sex organs in 196
- Metabolic disease**, in fish 216
- Metabolism**, effect on lifespan 101 104 124-126 129 136 137 169 170
- Mice**, amyloidosis in 80 81
 effect of diet on 79 80
 lifespan of 287
 white-footed lifespan of 95 96
- Miller's thumb**, lifespan of 223
- Minerals**, in pollen 237
- Minnow**, lifespan and size of 152
- Mitotic inhibitors**, 136
- Molecular changes in ageing**, 129 131
- Monkeys**, arteriosclerosis in 108
- Moontish**, lifespan of 221
- Mortality**, relation with age and growth 160-166
 theory of 127 129
- Mortality rates**, 286-296
 laws governing, 2 5
 mathematical models for 302 311
 sex differences in, 81
- Mosquito**, effect of diet on, 255
 lifespan of, 103
- Mosquito fish**, mortality rates of, 167
 reproduction and senescence in, 187-189
- Mothers**, age of, effect on lifespan, 25-27, 31 32
- Mugiloides**, lifespan and size of, 154
- Musca domestica** (see Housefly)
- Muscular degeneration**, 77
 in rats, 74-76
- Muskallunge**, lifespan of, 222
- Myocardial degeneration**, 77
 in rats, 74-76
- Myotis mystacinus**, lifespan of 97
- Neoplasia**, in fish 216 226
- Neothunnus macropterus** fecundity of, 193
- Nephrosis**, in man 77
 in rats 74-76 83
- Nerve cells**, in bees 234 244
- Nitrogen**, in pollen 236
- Odocoileus hemionus** lifespan of, 92 94
- Oncorhynchus nerka** fecundity in, 197-198
 growth of 156 157 158
- Oncorhynchus spp** mortality rates of 145
- Ophiocephaliformes**, lifespan of 224
- Orange chromide**, lifespan of 224
- Ovaries**, effect of age on in fish 201
 growth of in herring 195
 in bees 233 235 237 238 239 243
 of *Drosophila* 275 277 285
 in fish 193
 changes due to age 182
- Overwintering**, 232 234 240
- Ovis luli** lifespan of 92 94
- Owls**, lifespan of 99
- Palometa** lifespan of 220
- Parasites**, in fish 214 216 228
- Parental age** effect on fertility of offspring 36
 effect on lifespan 21 34 43 47 51 249 262
- Parental death**, in fish 189
- Parrots**, arteriosclerosis in 109 110
- Parus major** lifespan of 100
- Passer domesticus** lifespan of 99
- Passeres**, arteriosclerosis in 109
- Passerines**, lifespan of 99 100
- Pelecaniformes**, mortality rate of 101
- Pelicans**, arteriosclerosis in 109
- Penguin**, mortality rate of 100
- Perca fluviatilis** survival curves of 143 144
- Perch**, effect of diet 178
 lifespan and size of 154 220 223
 survival curves of 141 144 145
- Perciformes**, lifespan of 220 223 224
- Percoides**, lifespan and size of 154
- Peromyscus leucopus** lifespan of, 95-96

CUMULATIVE INDEXES TO VOLUMES 1-5

AUTHOR INDEX

| | | | |
|--------------------------------|------------------------------|------------------|------------------------------|
| Aas K | 4, 273, 294 | Amoroso, E. C | 1, 142, 159, 2, 1, |
| Aasen, O | 5, 149, 156, 174 | | 16, 27, 66, 67, 68, 83, 103, |
| Abbot, W. E. | 4, 109, 113 | | 106, 113, 115, 117, 125, |
| Abderhalden, E. | 4, 201, 202, 205 | | 126, 127, 128, 145, 155, |
| Abercrombie, M. | 3, 70 | | 158, 160, 173, 200, 240, |
| Abess, A. T. | 4, 127, 134 | | 241, 243, 246, 247, 253 |
| Abraham, K. | 1, 33, 43 | d'Ancona, U | 5, 167, 174 |
| Ackermann, F. G. | 1, 110, 121, 122 | Andersen, J | 5, 92, 94, 95, 102 |
| | 4, 241, 246 | Anderson, A. R. | 4, 301, 308 |
| Adair, F. | 2, 120, 121, 125 | Anderson, J | 1, 232, 234, 241 |
| | 127 | Anderson, J. L. | 3, 178, 181 |
| Adair, F. L. | 1, 151, 158, 160 | Anderson, W. E. | 4, 120, 121, |
| Adams, C. E. | 1, 143, 159 | | 128, 131, 135 |
| Adams, K. | 4, 91, 93 | Andersson, B. | 4, 37, 42, 56 |
| Addis, T. | 4, 254, 257, 259, 261 | Andrus, R. K. | 1, 168, 169 |
| Adlerberg, G. D. | 3, 136, 142 | Ando S. | 4, 68, 69, 72 |
| Adolph, E. F. | 4, 3, 4, 5, 6, 7, 8, 9, | Andrew | 4, 225 |
| | 10, 11, 12, 13, 14, 34, 34, | Andrew, W. | 5, 248, 264 |
| | 60, 73, 94, 95, 96, 97, 152, | Andrews, M. C. | 2, 129, 132, 143 |
| | 162, 195, 196, 221, 228, | Anitschlow, N. | 1, 89, 3, 101 |
| | 228, 311, 313 | Anger, G. | 4, 181, 195 |
| Aeby, H. | 1, 77 | Ansell, S. | 5, 21, 31 |
| Ahlman K. L. | 4, 74, 76 | Anslow, W. P. | 4, 277, 298 |
| Akyuz, E. | 3, 149, 174 | Antonissen, P. | 4, 41, 56 |
| Albertini, A. von | 1, 53, 55, 108 | Anthony, H. E. | 2, 184, 187 |
| Albertsen, S. R. | 4, 67, 68, 69, 72 | Appelboom, J. W. | 4, 24, 31 |
| Albright, F. | 1, 109, 122 | Appelget, J. | 5, 155, 174 |
| Alex, M. | 1, 91, 99, 103 | Arai, H. | 2, 32, 34, 51 |
| | 1, 97, 100 | Araki, Y. | 4, 68, 69, 72 |
| Alexander, F. | 3, 131, 142 | Arsaki, M. | 4, 251, 259 |
| Alexander, J. D. | 4, 275, 291 | Aristophanes | 1, 34 |
| Alexander, L. C. | 4, 289, 296 | Armbruster, L. | 5, 213, 241, 242 |
| Alexander, M. O. | 4, 40, 41, 57 | Arney, S. F. | 2, 206, 209 |
| Alexeyev, Berkman, I. A. | 4, 287, 295 | Aron, C. | 2, 36, 37, 38, 39, 41, 42, |
| Allen, W. C. | 1, 10, 14 | | 46, 47, 53, 60, 63, 66 |
| Allen, E. | 2, 38, 50, 57 | Aron, M. | 2, 60, 63, 66 |
| Allison, A. C. | 2, 235, 238 | Arons, W. L. | 4, 109, 112 |
| Allison, J. B. | 4, 131, 134 | Azora, H. L. | 5, 149, 174 |
| Allott, E. N. | 4, 38, 39, 41, 43, 56 | Azunkal | 2, 84 |
| Aller, M. S. | 5, 255, 264 | Arvidsson, V. B. | 3, 189 |
| Alm, G. | 5, 144, 155, 159, 168 | Ascher, B. M. | 3, 132, 143 |
| | 174 | Ascher, K. R. S. | 5, 235, 239, 264 |
| Alpatov, W. W. | 3, 21, 29 | Asdell | 1, 30 |
| Alman, A. I. | 1, 217, 231, 234, 238, | Asgood, H. S. | 5, 217, 264 |
| | 239 | Ashton, N. | 2, 30 |
| Alving, A. S. | 4, 243, 244, 246 | Asheton, R. | 2, 136, 138 |
| | 248 | Astbury, W. T. | 3, 96, 100 |
| Amatruda, T. T. | 4, 75 | Astrup, P. | 4, 41, 56 |
| American Academy of Pediatrics | 4, | Aub, J. C. | 1, 52, 54, 77, 104, 105, |
| | 160, 161 | | 124, 125, 205, 2, 178, |
| Amet, R. G. | 4, 4, 11, 19 | | 179, 180, 183 |

- Stress, 88
- Strigiformes, mortality rate of, 101
- Strix aluco*, lifespan of, 99
- Sturgeon, growth of, 156, 157, 158
lifespan of, 147, 220, 222, 226
lifespan and growth of, 163
lifespan and size of, 152
oldest age of, 191
reproduction in, 171
survival curves of, 143, 144
- Sugar, effect on bees, 238
- Sunfish, effect of environment of, 168
lifespan of, 223
protein metabolism in, 182-183
- Swifts, lifespan of, 100, 103, 104
- Syngnathiformes, lifespan and size of, 154
- Tarpon, lifespan of, 220
- Temperature, effect on bees, 245, 246
effect on cell, 281
effect on lifespan, 167-168
effect on lifespan in *Drosophila*, 271-279
- lifespan, 262
- Terms, lifespan of, 97-99, 104
- Tetodontiformes, lifespan of, 221
- Thunniformes, lifespan and growth of, 163
lifespan and size of, 154
- Thymallus signifer*, effect of environment on, 168
- Tits, lifespan of, 100
- Toadfish, lifespan of, 221
- Totoaba, lifespan and size of, 154
- Trigger fish, lifespan of, 221
- Trout, effect of diet on, 169, 253, 254
effect of reproduction on, 179
fecundity in, 192, 197
food conversion in, 186
growth rates of, 182
lifespan of, 222, 265
lifespan and size of, 150, 152
mortality rates of, 145
- Tuberculosis, in cows, 63, 64
- Tuna, fecundity in, 193
lifespan and size of, 154
- Ungulates, lifespan of, 91-95
- Vitamins, effect on bees, 238
in pollen, 237, 238, 239
- Vultures, arteriosclerosis in, 110
- Walleye, fecundity/length relationship in, 197
- Wasps, 232, 235
- Wax glands in bees, 233, 239
- Weakfish, lifespan of, 221
- Whitebait, lifespan and size of, 150
mortality rate of, 146
- Whitefish, growth of, 156, 157, 158
lifespan of, 222
lifespan and size of, 150
survival curves of, 143, 144
- Whiting, lifespan and size of, 154
- Yellow tail, lifespan of, 221

| | | | |
|-------------------|-------------------------|-------------------|-------------------------|
| Bilis, L. de | 4 242 246 | Boyd E. M | 2, 122 125 |
| Binet A. | 3 176 182 | Boyd, H. | 4 101 102 |
| Birch Andersen A. | 4, 1 6 136 | Boyd J. D. | 2, 185 186 |
| Birchard W. H. | 4 51 56 | Boyle, A. J. | 4 239 296 |
| Birren, J. E. | 1 38 48 | Boyne A. W. | 1 196 199 |
| Bischoff F. | 4, 262 | Boze, B. | 2, 11 13 17 |
| Bishop L. R. | 2, 206 209 | Brachet, J. | 1 192 193 |
| Biskind G. S. | 1 153 160 | Bradley G. P. | 4 274 294 |
| Biskind M. S. | 1 153 160 | Bradley S. E. | 4, 274 275 294 |
| Bittner J. J. | 1 153 160 | Bradbelt F. W. R. | 2, 34 59 53 |
| Bjorkman N. | 2, 155 156 158 | | 57 60 66 81 83 |
| Bjorksten J. | 3, 66, 67 | Brand F. C. | 4, 23 32 |
| Black, A. | 4 127 135 | Brandfonbrener M. | 1 237 3 77 84 88 |
| Black D. A. K. | 4 13 38 40 41 50 | | 89 90 91 4 234 236 246 |
| | 56 57 59 59 75, 113 150 | Brandt F. A. | 3 102 |
| | 150 163 208 224, 226 | Brannon E. S. | 4 279 297 |
| | 247 248 264 267 268 | Breder C. M. | 5 212 217 218 225 |
| | 269 310, 317 | Breed E. S. | 4, 274 297 |
| Blackburn M. | 5 146 149 151 173 | Bretherick Q. | 5 237 243 |
| Blackman F. F. | 2, 205 | Breward M. M. | 2, 33 53 |
| Blair W. F. | 5, 96 102 | Brewer W. D. | 1 122 123 |
| Bake W. D. | 4 273 287 294 | Bricker N. S. | 4 45 56 |
| Blalock, A. | 4, 287 296 | Brien, P. | 1 244 |
| Bland J. H. | 4 294 | Briggs, A. P. | 4 275 277 295 |
| Blandan, R. J. | 1 149 2, 81 83 85 | Briscoe, W. A. | 4 264 268 |
| Blaxter K. L. | 4 301 307 08 309 | Brook, J. | 4, 248 271 272 273 279 |
| Blazka P. | 5 170 175 | | 281 284 286 288 295 296 |
| Blegen E. | 4, 273 294 | Brodsly W. A. | 4 24 31 40 |
| Bloch, E. | 4 90 93 | | 46 57 |
| Bloom, W. L. | 4 127 134 | Brody M. B. | 3 173 182 |
| Blum H. P. | 2, 228 231 | Brody S. | 1 188 189 190 193 |
| Boas, E. P. | 3, 136 142 4, 136 142 | | 197 199 5 124 132 |
| Bodenheimer F. S. | 5 294 | Brooks, D. | 3 70 96 100 |
| Bötcher T. | 5, 60 61 69 | Brooks, L. | 4 109 113 |
| Bogdonoff M. D. | 1 110 120 121 122 | Bro-Rasmussen, F. | 4, 63 65 68 73 |
| | 3 78 90 4, 226 | Brown, A. N. | 4, 131 135 |
| Bogomolets, A. A. | 3 133 142 | Brown, C. J. D. | 3 76 29 5 168 175 |
| Boling, E. A. | 4, 102 106 108 113 | Brown I. W. | 2, 234 238 |
| Bommer S. | 2, 191 198 | Brown L. M. | 4, 46 57 |
| Bondurant, J. | 4, 109 113 | Brown M. E. | 5 147 148 149 175 |
| Bondy E. | 1 42 48 3, 137 143 | | 217 225 |
| | 173 182 | Brown R. A. | 3 151 |
| Bondy P. K. | 4 257 259 | Brozek J. | 4 157 161 162 |
| Bongiorno A. M. | 4 80 92 | Brubacher Z. | 2, 171 183 |
| Bonin G. von | 5, 119 1 3 128 132 | Bruce, R. A. | 4, 46 56 |
| Bonner J. | 2 208 209 | Bruce, A. M. | 5 138 |
| Boog, J. M. | 4, 89 92 93 | Bruh n H. | 2, 177 181 183 |
| Boelter L. E. | 4 132 135 | Brull, L. | 1 27 68, 123 124 202, |
| Boel, L. M. | 3 117 118 120 123 | | 207 238 241 |
| | 124 125 | Bryden J. G. | 3 107 114 |
| Boeoughs, H. | 5 170 175 | Bryuzgin V. L. | 3 17 18 |
| Borst, J. G. G. | 4, 60 101 114 196 | Buchanan, A. D. | 5 59 69 |
| | 248 260, 261 269 298 | Buchborn, E. | 4 280 292 293 295 |
| Borum E. R. | 4 200 205 | Bucher G. E. | 5 258 264 |
| Bowrick J. | 3 151 168 | Bucht, H. | 4 273 279 280 283 |
| Bounoure | 2, 56 | | 295 298 |
| Bouriere F. | 2, 183 210 211 247 | Buchwald, N. A. | 3, 136 142 |
| | 247 248 249 3 10 17 18 | Buehl C. C. | 1 158, 201 |
| | 20 28 29 31 129 5 70 | Buehler C. | 1 49 |
| | 84, 91 96 102 103 104 | Buettoer K. | 4, 100 |
| | 105 112, 113 119 132 | Bu ard, E. | 2, 42 53 |
| | 137 217 225 227 228 245 | Bu l, G. M. | 4, 265 268 |
| Bourne, G. H. | 3 34 35 47 50 68 | Bull J. P. | 4, 98 98 115 153 151, |
| | 72, 130 144 188 189 | | 163 207 228 249 269 |

- Aumonier, F. J. 3, 56
 Austin, C. R. 2, 86, 96
 Austin, O. L. 5, 98, 102
 Austin, O. L. Jr. 5, 98, 102
 Axclrad, B. J. 4, 292, 294, 297
 Babcock, H. 3, 179, 181
 Babkin, B. P. 4, 62, 72
 Back, E. 5, 235, 238, 241
 Baclesse, M. 2, 168, 172
 Bacon, F. 3, 9, 18
 Bacsich, P. 1, 142, 159; 2, 41, 53
 Bagenal, T. B. 5, 192, 193, 200, 201, 202, 205, 207
 Bailey, M. 4, 146, 147, 149
 Baillie, W. H. T. 3, 24, 29
 Baimey, J. D. 4, 109, 112
 Baird, D. 5, 33
 Baker, B. L. 4, 260
 Bale, W. F. 2, 263, 238
 Balfour, W. M. 2, 236, 238
 Balinsky, B. 1, 37, 38, 48, 3, 178, 181, 186
 Ball, M. R. 4, 114, 291, 297
 Ball, Z. B. 1, 180, 185
 Ballon, J. 1, 219, 223, 224, 225, 227, 232, 233, 236
 Balò, J. 1, 98, 99, 103, 104, 107, 3, 32, 44, 70, 97, 98, 100, 101, 101, 103
 Banfield, A. W. F. 5, 92, 102
 Banga, I. 1, 98, 99, 103, 104, 107, 3, 65, 66, 67, 97, 98, 100, 101, 103
 Banta, A. M. 3, 24, 29
 Barber, J. K. 4, 89, 92, 292, 293, 294, 297
 Barbour, A. 4, 265, 268
 Barcroft, Sir J. 2, 126, 151, 153, 5, 133
 Barker, J. P. 4, 3, 4, 11
 Barker, S. B. 2, 130, 143
 Barlow, J. S. 4, 106, 112
 Barnes, B. A. 4, 49, 56
 Barnes, L. L. 1, 183, 197, 197, 200, 3, 8, 18, 5, 251, 264
 Barnes, R. H. 1, 180, 185
 Barnett, H. A. R. 5, 5, 15
 Barr 1, 89
 Barrett, G. R. 1, 149, 160
 Barrett, M. K. 3, 123, 124
 Barron, D. H. 2, 118, 125
 Barrows, C. H. 4, 245, 246
 Bassett, D. L. 2, 60, 66
 Bates, D. V. 1, 58, 62, 64, 65
 Bauer, K. 5, 59, 69
 Bauer, L. S. 4, 133, 134
 Bartholomew, R. A. 2, 112, 113
 Bartlett, Sir F. C. 1, 41, 202, 204, 214, 215, 216, 217, 218, 246
 Barton, R. A. 5, 53, 54
 Bartler, F. C. 4, 46, 57, 89, 97, 196, 280, 292, 293, 294, 297
 Beams, H. W. 2, 86, 96
 Bean, H. W. 4, 120, 121, 131, 135
 Bean, W. B. 1, 78, 79, 80, 87, 105, 171
 Beard, R. E. 5, 4, 14, 285, 239, 302, 303, 305, 307, 308, 311
 Beck, J. C. 4, 293, 294
 Becker, W. H. 4, 273, 293
 Beeton, M. J. 5, 21, 31, 33, 53, 54
 Belding, D. L. 5, 197, 207
 Bell, F. H. 5, 151, 177
 Bell, R. G. 1, 196, 200
 Bendell, J. F. 5, 101, 102
 Benedict, F. G. 3, 9, 18; 4, 138; 5, 124
 Bencke, R. 5, 110, 112
 Benjamin, B. 1, 198, 199; 5, 2, 15, 16, 17, 18, 19, 32, 34, 70, 293
 Bennett, H. S. 2, 106, 112, 114, 129, 144
 Bensley 2, 103
 Bercu, B. A. 4, 280, 294
 Berdegue, J. 5, 155, 175
 Berg, B. N. 5, 16, 32, 33, 72, 73, 74, 75, 76, 79, 79, 80, 82, 83, 84, 85, 86, 87, 88, 114, 137, 265, 266, 283
 Berg, L. S. 5, 212, 225
 Bergerard, Y. 2, 11, 13
 Bergmann, K. 4, 284, 286, 297, 298
 Bergstrom, J. 4, 293
 Bergstrom, W. H. 4, 120, 134
 Berkeley, A. 1, 219, 223, 224, 225, 226, 227, 232, 233, 236
 Berman, C. 3, 106, 114
 Bernard, C. 1, 205, 2, 23, 27, 108, 113, 118, 137
 Bernhard, K. 2, 177, 183
 Bernstein, F. 3, 195
 Bertalanffy, L. von 5, 157, 169, 175
 Berthet, J. 2, 136, 143
 Bertholf, L. M. 5, 235, 241
 Bertin, L. 5, 168, 173
 Bertuccio, M. 4, 140, 141, 146, 149
 Best, A. T. 5, 104
 Best, C. H. 3, 1, 36, 46, 49, 101, 103, 126, 127, 128, 146, 147, 182, 188, 192, 195
 Beutler, R. 5, 235, 238, 241
 Blevan, W. 4, 127, 134
 Beverton, R. J. H. 5, 142, 149, 151, 153, 175, 177, 178, 179, 226, 227, 229
 Bezem, J. J. 5, 97, 103
 Biale, J. H. 2, 208, 209
 Bichat, A. 1, 245
 Biddet, G. P. 1, 28, 3, 9, 18, 5, 173, 175, 182, 189, 190, 197, 207
 Bienvenu, D. 1, 164, 200
 Bilewicz, S. 5, 277, 291
 Billeter, J. R. 4, 181, 193
 Billingham, R. E. 1, 170, 2, 229, 231, 3, 116, 124

| | |
|-------------------|--|
| Cooke W T | 4, 109 112 |
| Cooper A. R. | 4 120 121 135 |
| Cooper E. L. | 5 144 153 176 |
| Cooper I S | 4, 39 40 41 43 56 |
| Cooper K. E | 2 120 121 125 |
| Cope O | 4, 49 56 |
| Copenhagen J H | 4 209 219 |
| Coquiom-Carnot, M | 4, 217 219 |
| Co bo, S. | 1 199 200 |
| Corey E. L. | 2, 109 113 |
| Corkins, C. L. | 5 245 |
| Corrado, L. | 1 194 200 |
| Corbleet, T | 2, 197 198 |
| Corner G W | 2, 15 55 56 64 66
67 246 252 |
| Corsa, L. | 4 105 113 114 143 149 |
| Cort, J H | 4 33 45 56 214 219
222 278 283 287 288
89 291 292 295 |
| Cotes, P M | 2, 162 172 |
| Cotillo E. | 4, 129 135 |
| Count, E. W | 5 119 123 132 |
| Court, D M | 3 95 100 |
| Cournol, L. | 4 262 |
| Courner R | 2, 116 168 172 |
| Coville F E | 4, 133 134 |
| Cowan, G A | 3 55 56 |
| Cowdry E. V | 1 24 26 27 50, 53,
55 88 103 108 171 172,
204 205 207 242, 243
2, 111 112 113 |
| Cowie D B | 4, 280 298 |
| Crabbe, J | 2, 23 27 122 125 |
| Crame W | 4 260 |
| Crane W A J | 1 198 200 |
| Cravio o Muñoz, J | 4, 51 56 |
| Crawford H | 2 216 226 231 237 238 |
| Crawford J D. | 4 139 140, 141
146 147 149 |
| Cressen, A. | 3 137 142 |
| Cretter P H | 4 39 40 43 56 |
| Crocy, A P | 4 289 297 |
| Crowell, M F | 1 197 200 3, 25
29 5 169 176 251 253
254 |
| Crozier W J | 5 257 |
| Cruckshank D H | 2 203 210 |
| Crump er H R. | 2, 112 123 |
| Cruz, W O | 2 236 238 |
| Czapó J | 4 155 161 |
| Cummings, J | 4 46 56 |
| Cuny G | 4 242 246 |
| Currie C | 1 198 201 |
| Curtis | 5 87 |
| Curtis, R H | 4 292 297 |
| Curzon E. G | 4 131 135 |
| Cushum M | 2, 216 276
231 237 238 |
| Cuthbertson D P | 4 130 135 |
| Dacie, J V | 4, 199 205 |
| Dack S | 3 75 90 |
| Daines, M. C | 4 266 268 |
| Dalton, K. | 4 84 93 |

| | |
|--------------------|--|
| Dal on N N | 2, 228 232 |
| Daly C. | 5 21 31 |
| Daniells, J F | 3, 39 43 45, 46 47
48 49 50 68 96 129 130
144 148 185 5 1 15 17
19 32, 33 34 70 103 104
114 133 136 137 177
178, 209 229 230, 281
282, 298 |
| Danowski T S | 4, 289 295 |
| Darrow D C. | 4 106 113 133 134 |
| Dasmann, R. P | 5 92 94 103 |
| Davey W P | 5 282 |
| Davison F J | 3 107 |
| Davison, J N | 1 191 193 |
| Davies, B. M A | 1 192 193
209 219 |
| Davies, C. E. | 4, 66 268 |
| Davies, D F | 1, 270 236 3 88
90 5, 72 |
| Davies, H E. F | 4, 130 266 268 |
| Davis, D E | 5 95 102 |
| Davis, G K. | 2, 148 159 |
| Davis, J E. | 1 206 |
| Davis, J M | 4, 102 106 108 113 |
| Davis, J O | 4, 277 295 |
| Davis, W S | 5, 192 207 |
| Davson, H | 4 15 20 28 29 31
32, 33 34 35 58 59 73
96 99 100 101 114 162,
206, 207 208 269 309
312, 315 316 |
| Dawes, G S | 2, 104 115 125 126 |
| Dawson, A B | 2, 81 83 |
| Dean R. F A. | 1 198 200 |
| Deane H W | 2, 23 26 37 53
60, 66 |
| Deason H J | 5, 151 176 |
| De Du c, C | 2, 136 143 |
| Deelder C. L. | 5, 159 175 |
| Deevey E. S | 1 10, 15 5 91 102 |
| De dar R. | 4, 291 296 |
| De Jongh, S E. | 2, 64 66 |
| De la Baze F A. | 2, 86 96 |
| Del Castillo, E. B | 1 151 160 |
| Delea, C | 4, 89 92 292 293 294 297 |
| Deming O B | 4 280 293 297 |
| Dempsey E. W | 1 103 2, 41
54 54 57 60 66, 67 68
100 103 104 106 107
109 110 111 113 114
129 144 146, 147 186
191 192 198 241 243,
246, 248 250 251 253 |
| Dennis, W H | 4 24 31 |
| Dent, C. E. | 2, 112 113 |
| Deringe M K | 3, 121 123 124 |
| Desaulles P A | 4 59 60 76 94
180 181 187 188 194
195 196 197 198 206,
227 228 262, 316
5, 67 69 |
| De kens | 3, 102 103 |
| Dettmer | 5 149 173 |
| Devold, F | |

- Bullough, W S. 2, 38, 53, 64, 66
 Bulmer, M G 4, 65, 69, 73, 74
 Bunge, R G 1, 171
 Bunting, H 2, 191, 192, 198
 Burch, H 1, 197, 199
 Burd, A C 5, 149, 175
 Burgess, A S V 4, 64, 73
 Burger, M 3, 6, 18
 Burgess, E. W 1, 43, 43
 Burgos, M H 2, 86, 87, 96
 Burki, W 2, 36, 42, 43, 44, 53
 Burn, G B 2, 235, 238
 Burnett, F M 2, 228, 231
 Burns, C. M 5, 21, 31
 Burrill, M W 2, 12
 Burrows, H 2, 49, 51, 53
 Burton, D 3, 97, 100
 Bush, I E. 4, 181, 194
 Butler, A M 4, 139, 141, 147, 149
 Butler, C. G 5, 237, 241, 243
 Butt, W R 1, 130, 137
 Buxton, P A 5, 240, 241
 Byers, S. O 3, 137, 142
 Bykov, A. M 4, 287, 295
 Byrom, F B 4, 258, 259

 Caldwell, M J 4, 200, 205
 Caligaris, L. C. S 4, 89, 93
 Calloway, D H 4, 131, 134, 135
 Calvin, M 2, 223, 232
 Cameron, G R 1, 16, 26, 54
 55, 66, 3, 93, 100
 Cameron, J W McB 5, 258, 264
 Cameron, W 1, 51
 Campbell, H A 1, 197, 200
 Campbell, R. M 2, 166, 172
 Canvenc 2, 175
 Cannon, C 5, 39, 69
 Cannon, P R 4, 133, 134
 Capek, K 4, 165, 179
 Card, W I 4, 301, 309, 310, 317
 Carlo, J 1, 126, 137, 219, 223, 224
 225, 226, 227, 232, 233
 236, 4, 90, 93
 Carlsen, E. 4, 46, 56, 264, 268
 Carlson A J 1, 197, 199, 206
 Carlson L D 5, 89
 Carter, S. B 3, 51, 59
 Castle, W E. 1, 155, 160
 Cathcart, E. S. 4, 291, 295
 Caton, J D 2, 179, 181
 Caton, W L 2, 166, 172
 Cavan, R S. 1, 43, 48
 Cavanaugh, M W 2, 3, 10, 11, 13
 Cavazzana, P 2, 191, 196, 198
 Challice, C. E. 2, 86, 96
 Chalmers, T A. 5, 56
 Chaloupka M 1, 122, 123
 Chang, H W 5, 145, 146, 153, 175
 Chaplin, H 1, 164, 169, 2, 216,
 226, 231, 232, 238, 255
 4, 166, 179
 Chaplin, J P. 1, 156, 199
 Chapman R. N. 4, 193, 194, 195, 256
 Chase, H B. 2, 191, 192, 194, 199
 Chasis, H. 4, 230, 245
 Check, D B 4, 105, 109, 113, 120,
 121, 132, 133, 134
 Chesley, L. C. 4, 82, 84, 89, 92, 93
 Chevremont 2, 103
 Chibnall, A C 2, 204, 209
 Chipman, W A 5, 170, 173
 Chitty, H 3, 10, 13, 5, 103,
 296, 298
 Chow, B F 1, 198, 199, 3, 79,
 91, 4, 243, 246
 Christensen, P R 1, 40, 43
 Christie, R V 1, 58, 61, 62, 63, 65,
 66, 67, 68, 243
 Chugacva, M 5, 51, 54
 Ciba Foundation 5, 153, 152
 Claesson, I. 2, 60, 66
 Clara, M 1, 54
 Clark, F N 5, 149, 155, 175
 Clark, H W 5, 212, 226
 Clark, J 1, 239, 240
 Clarke 5, 266
 Clarke, J M 5, 278, 281
 Clarke, R D 5, 4, 5, 6, 7, 8, 10,
 11, 14, 15
 Clay H M 3, 155, 162, 168
 Clermont Y 2, 86, 96
 Cloette 2, 159, 160
 Cochran W 4, 139, 141, 147, 149
 Cockrum, E L 3, 27, 29
 Cohen A 2, 22, 23, 26
 Cohen B L 4, 202, 203, 205
 Cohen D M 5, 151, 173
 Cohen, H W 4, 51, 57
 Cohen J 4, 132, 133, 135, 227
 Cohn, J E 4, 243, 244, 246
 Cohrs P 5, 110, 112
 Cole D F 4, 193, 194
 Collazon, Ch J I 1, 109, 121, 122
 Colonge, R M A 2, 3, 13, 34, 163, 171
 Comfort, A 1, 28, 29, 30, 51, 52,
 107, 138, 171, 204, 238,
 241, 242, 243, 244, 245
 2, 215, 231, 3, 2, 7, 11, 12,
 18, 29, 30, 36, 37, 38, 46,
 68, 118, 124, 4, 17, 17, 32,
 34, 35, 36, 37, 43, 44, 47,
 52, 53, 54, 55, 56, 70, 71,
 84, 85, 87, 88, 103, 104,
 113, 114, 116, 117, 119,
 132, 134, 136, 137, 169,
 173, 175, 178, 179, 203,
 208, 209, 210, 217, 225,
 227, 229, 230, 244, 262,
 264, 265, 266, 286, 286,
 289, 291, 294, 295, 298
 Comroe, J H 4, 264, 268
 Conn, J W 4, 44, 56, 76, 240, 291
 Conrad, H S 3, 171, 182, 186
 Conway, L. J 4, 22, 23, 24, 11, 33, 69,
 203, 205, 207, 226
 Cook, C D 4, 103, 113, 141, 149
 Cooke, R L 4, 153, 154

CUMULATIVE AUTHOR INDEX

5

| | | | |
|-------------------|------------------------|-------------------|-------------------------|
| Cooke W T | 4 109 112 | Dalton, N N | 2, 228 232 |
| Cooper A. R. | 4, 120 121 135 | Daly C. | 5, 21 31 |
| Cooper E. L. | 5, 144 153 176 | Daniel, J F | 3, 39 43 45 46 47 |
| Cooper I S | 4 39 40 41 43 56 | | 48 49 50 68 96 119 130 |
| Cooper A. E. | 2, 120 121 125 | | 144, 148 185 5, 1 15 17 |
| Cope, O | 4 49 56 | | 19 32, 33 34 70 103 104 |
| Copenhagen J H | 4 209 219 | | 114 133 136, 137 177 |
| Coquoin-Carnot, M | 4 217 219 | | 178 209 229 230, 281 |
| Corbo S | 1 199 200 | | 282, 298 |
| Corey E. L. | 2, 109 113 | Danowak T S | 4, 289 293 |
| Corkins, C. L. | 5 245 | Darrow D C | 4 106, 113 133 134 |
| Cornaro L | 1 194, 200 | Dastmann R P | 5 92 94 103 |
| Cornbleet, T | 2, 197 198 | Davey W P | 5, 32 |
| Cornier G W | 2, 15 55 56 64 66 | Davieson F J | 3, 107 |
| | 67 246 252 | Davidson, J N | 1 191 192 |
| Corsa, L. | 4, 105 113 114 143 149 | Davies, B M A | 1 192 193, |
| Cort, J H | 4, 33 45 56 214 219 | | 209 219 |
| | 222 278 283 287 288 | Davies, C. E. | 4, 266 268 |
| | 289 291 292 295 | Davies, D F | 1 220 236 3 68 |
| Cotes P M | 2, 162 172 | | 90 5, 72 |
| Cotlo e E | 4, 129 135 | Davies, H E. F | 4 150 266 268 |
| Count, E. W | 5 119 123 132 | Davis, D E. | 5 95 102 |
| Court, D M | 3, 95 100 | Davis, G K | 2, 148 159 |
| Cournat, L. | 4 262 | Davis, J E. | 1 206 |
| Courrier R. | 2, 126 168 172 | Davis, J M | 4, 102 106 108 113 |
| Coville F E. | 4, 133 134 | Davis, J O | 4, 277 295 |
| Cowan G A | 3 55 56 | Davis, W S | 5, 192 207 |
| Cowdry E. V | 1 24 26 27 50 53 | Davson, H | 4 15 20, 23 29 31 |
| | 55 68 103 108 171 172, | | 32, 33 34 35 58 59 73 |
| | 204 205 207 242, 243 | | 96 99 100 101 114 162, |
| Cowle D B. | 2, 111 112 113 | | 206 207 208 269 309 |
| Crabbé J | 4 280 298 | | 312, 315 316 |
| Cramer W | 2 23 27 122 125 | Dawes, G S | 2, 104 115 125 126 |
| Crane, W A J | 4 260 | Dawson A B | 2, 81 83 |
| Cravioto Muñoz, J | 1 198 200 | Dean, R. F A | 1 198 200 |
| Crawford B | 4 51 56 | Deane H W | 2, 23 26 37, 53 |
| Crawford H | 2 216 226 231 237 238 | | 60 66 |
| Crawford J D | 4 139 140 141 | Deason, H J | 5 151, 176 |
| | 146 147 149 | De Du e, C | 2, 136 143 |
| Cresser, A. | 3 137 142 | Deelder C. L. | 5, 159 175 |
| Cretter P H | 4 39, 40, 43 56 | Deevey E S | 1 10 15 5, 91 102 |
| Crosby, A P | 4, 289 297 | Dejdar R. | 4, 291 296 |
| Crowell M F | 1 197 200 3, 25 | De Jongh, S E. | 2, 64 66 |
| | 29 5, 169 176 251 253 | De la Blazé F A | 2, 86 96 |
| | 254 | Del Castillo E. B | 1 151 160 |
| Crozier W J | 5 267 | Delea, C | 4 89 92 292 293 294 297 |
| Cruckshank D H | 2, 203 210 | Deming, Q B | 4, 280 293 297 |
| Crumpler H R. | 2, 112 113 | Dempsey E W | 1 103 2, 41 |
| Cruz, W O | 2, 236 238 | | 54 54 57 60 66 67 68 |
| Caapo, J | 4 155 161 | | 100 103 104 106 107 |
| Cummins, J | 4 46 56 | | 109 110 111 113 114 |
| Cuny G | 4, 242 246 | | 129 144 146 147 186 |
| Currie C | 1 198 201 | | 191 192 198 241 243 |
| Curtis | 5 87 | | 246 248 250 251 253 |
| Curtis, R H | 4 292 297 | Dennis W H | 4 24 31 |
| Curzon E. G | 4, 131 135 | Dent, C. E. | 2 112 113 |
| Cutbush, M | 2, 216 226 | Derogier M K. | 3, 121 123 124 |
| | 231 237 238 | Desaullès, P A | 4 59 60 76, 94 |
| Cuthbertson D P | 4 130 135 | | 180, 181 187 188 194 |
| | | | 195 196 197 198 206, |
| Dacie, J V | 4 199 205 | | 227, 228, 262, 316 |
| Dack S | 3 75 90 | Detkens | 5, 67 69 |
| Daines, M C | 4 266 268 | Detmer | 3, 102 10 |
| Dalton, A. | 4, 84 93 | Devold F | 5 149 17 |

- Dewar, M M 4, 10, 11
 Deyrup, I 4, 24, 31
 Diamond, L 4, 24, 31
 Dice, L. R. 3, 10, 18
 Dickerson, J W T 4, 217, 219
 Dickie, L. M. 5, 151, 175
 Dieckmann, W J 2, 112, 113
 Dietrich, H. 5, 60, 69
 Dilley, W E. 1, 197, 200, 5, 169, 176
 Dinkhauser, F 5, 63, 69
 Djouha, H 4, 9, 10 11, 165 179
 Dobner, A 1, 133 137
 Dobson, E. L. 4, 289, 295
 Dodson 3, 185
 Dossy, E. A. 2, 50 53
 Dole, V P 4, 67, 73, 77
 Doljanski, I 5, 208
 Donohue, D 4, 46 56
 Donohue, D M 2, 237 239
 Dorfman, R. I 1, 126 130, 134 137 4, 90, 93 137 195
 Dornhorst, A C 2, 234 238
 Dorst, J 3, 27, 29
 Douglass, P M 1, 156, 161
 Downing, D F 1, 198 200
 Doyle, A E. 4, 278 295
 Dreizen, S 1, 188 200
 Drescher, A N 4, 145 149
 Droop, M R 1, 187 193
 Drummond, J A 3, 107
 D Silva, J L. 2, 148 148, 149 150 158
 Dublin, L. I 1, 195, 200 203 2, 85 90 137 142
 Dubois, A B 4, 264 268
 Dubois, E. 5, 123 132
 Duckworth, J 2, 184 187 4, 309
 Duesberg, J 2, 86 93 96
 Duetz, G H 5, 85
 Duncan, L. E. 1, 139 3, 78 90 4 89 92 226 250 292 293 294, 297
 Dunewitz, A 1, 198 200
 Dunham, L. J 1, 151 158 160
 Dunn, Th. B. 3, 121 122 124
 Dunning, M F 4, 46 56
 Dupret, L. 2, 136 143
 Dyke, H B. van 4, 92 91
 Dymond, J R. 5, 175
 Dyrenfurth, I 4, 89 93 293 294
 Eadie, G S. 2, 234 238
 Earle, D F. 4, 275 295
 Eberlein, W R. 4, 80 92
 Economou Mavrou, C 4, 218 219
 Eddy, M. 3, 160
 Edelman, I S. 4, 36 47 56 109 113 280 293 5, 169 175
 Edmonds, S J 1, 196 200
 Edmonds, T R 1, 111 114 115
 Leg Larson, N 120, 122 123 4, 119, 135
 Eichna, L. W 4, 275 295
 Eidrigevits, E. V 5, 53 54
 Einstein, A 2, 227, 231
 Eisenberg, S 4, 233, 268
 Ek, J 4, 273, 279, 280 281 293, 298
 El Deeb A L. A 5, 232, 234, 241
 Eliasch, H 4, 273, 279, 280, 281 293, 298
 Elikin, R 5, 168, 176
 Elikinton, J R 4, 38, 46, 56, 259 295, 297
 Elliott R H 2, 120, 125
 Ellis, R S 5, 248, 264
 Elmajian, F 1, 219, 219, 223, 224 225 226 227, 240, 252, 233, 234, 236
 Elrick, H 1, 199 200
 Emsdon Dew, R 3, 185
 Elvehjem, C A 1, 197 200, 4, 133, 136
 Ely, R S 4, 105, 113
 Emerson A E 1, 10, 14
 Engel S L 4, 92 93, 257 259
 Engeler W 4, 59, 69
 Engfeldt B 2, 162, 172
 Engle L. T 1, 157, 160, 2, 60 66
 Engstrom W W 4, 42 56
 Enzmann E. V 2, 36 37, 54
 Epstein F H 4, 46 57
 Erickson D W 5, 196, 197 208
 Ershoff B A 1, 197 201
 Escher D J W 4, 277 280 293 297
 Eschmeyer P H 5, 197 207
 Essen Moller L. 3, 134, 142
 Etheridge J 4, 109, 113
 Evan, J V 4, 201, 202 203, 205, 221
 Evans, B M 4, 265 268
 Evans, C A 5, 297
 Evans, H 5, 92 102
 Evans, H M 1, 29 2, 41 53
 Evans, W A 4, 241 246
 Eversius, C 5, 232 241
 Everett, N B 2, 34 53
 Evermann B. W 5, 212 276
 Ewing G 4, 283 296
 Fahmy 2, 123
 Fahr, H O 5, 110 113
 Failla A 5, 239
 Fairstat T D 2, 19 25 168 172
 Fairbaird A. 4, 292 291 295
 Falek A 3, 115 119 121
 Fala G 4, 6 11 11 11 167 169 172 179
 Faltzone J A 3, 75 90
 Farber S J 4, 275 291
 Fargo W C 1, 191 201
 Farner D S 5, 6 101 102 103
 Farr, W 5, 9

| | | | |
|--------------------|------------------------|---------------------|-------------------------|
| Farran, G P | 5, 194 207 | Foulds, G | 3, 160 168 |
| Farrar C. L. | 5 232 234 241 | Fountaine M. E. | 3 23 29 |
| Fawcett, D W | 2, 86 87 96 97 98 | Fouracre Barns, H H | 2, 174 |
| | 99 103 104 109 114 129 | Fourman, P | 4, 36, 44 37 59 60 |
| | 144 177 183 250 | | 95 97 113 138, 151 163 |
| Fazekas | 3 147 | | 164 196 196 197 206 |
| Fearce J P | 2, 148 159 | | 221 224 225 262, 263, |
| Fengold L | 1 42 48 3 137 143 | | 301 308 309 309 316 |
| Fengold Jarvik | 3, 139 | Fowell, D M | 4, 275 277 295 |
| Fejfar Z | 4 32 33 115 163 248, | Foy H | 3 189 |
| | 261 271 271 272 273 | Fox, H | 1 88 5 103 109 112 |
| | 279 281 282 284 286 | Frabick R. L. | 2, 3 10 13 |
| | 291 295 296 298 299 | Franca, P da | 5 133 173 |
| | 300 317 | Frank, F | 5 62 69 |
| Fejfar J, M | 4 281 284 286 291 | Frankland H M T | 5 53 54 |
| | 295 296 | Franklin K. J | 1 31 65 76, 77 79 |
| Fekete, E. | 1 146 150, 156, 160 | | *02, 205 214, 242, 245, |
| Feldman Mubsam, B | 5 259 264 | | 3, 51 52 59 71 72, 126 |
| Fell, H. B. | 2, 4 12 | Fraser D | 2, 174 |
| Fench, V | 4, 278 289 295 | Fraser E. A | 5 189 207 |
| Ferngold, L. | 3 173 182 | Fraser F C | 2, 19 26 168 172 |
| Felding, U | 2, 50 53 | Fraser R | 4, 301 308 |
| Ferguson W G | 4 200 205 | Franz, V | 5 202 207 |
| Fier L. J. | 4, 133 134 | Frederic | 2, 103 |
| Fitch C. A. | 2, 228 229 231 232 | Freeman, H | 1 36, 50 51 52, |
| | 237 238 | | 137 138 139, 219 219 |
| Fack M A. von | 4 211 212 219 | | 223 224 225, 276 277 |
| Fadlay G H | 3 102 | | 230 232 233, 234 236 |
| Finkel, M P | 2, 148 158 | | 236 237 238, 4, 90 93 |
| Fonell, J | 5, 168 176 | Freudenberg, F | 5 62 69 |
| Ficket, H | 2, 62 66 | Freudenstein H | 5 235 236 237 241 |
| Fischer A | 3 32 | Freudenstein, K. | 5, 232 241 |
| Fischer Piette, E. | 3 25 29 | Freydberg, V | 3 67 |
| Fisher A. J. | 4 98 | Friedemann, T E. | 2, 130 143 |
| Fiske C H | 4, 120 135 | Friedman, M | 3, 133 142 |
| Fister H J | 4, 120 135 | Friedman, R | 3 75, 90 |
| Fitch H S | 5 96 97 102 | Friedman S M | 3 45 128 146 |
| Fitch, J E. | 5 155 175 | | 184 192 |
| Fitzgerald M G | 4, 301 308 309 | Frus Hansen, B J | 4, 102, 103 |
| Flade, J E. | 5 66 69 | | 105 109 115 114 143 |
| Fletcher H M | 4, 63 73 | | 149 |
| Flexner L B | 2, 109 111 113 | Friley M | 2, 167 172, 3 11 13 |
| | 118 125 148 158 159 | Froesch E. R. | 4 280 298 |
| | 4 26 31 | Frontal G | 1 199 200 |
| Fluk, E B | 4, 301 308 309 | Frost, W E. | 5, 153 175 |
| Flint, M H | 3 70 | Funaro R | 1 199 200 |
| Flipse, R J | 4 200 205 | Fry D H | 5 168 170 175 |
| Flower S | 5 119 128 132 168 175 | Fry F E. J | 5 192 207 |
| | 277 225 | | |
| Floyer M A | 4 258 259 | Gaarenstroom J H | 2, 64 66 |
| Flückge E. | 3, 64 68 | Gabrio B W | 2, 228 229 231 232 |
| Foa C | 1 151 155 160 | | 237 238 |
| Foldi, M | 4 45 57 284 286 296 | Gakkel L. B | 3 133 142 |
| Foerster R E | 5 151 156 175 | Gale, E. F | 1, 287 192 193 |
| Foer, G E | 1 185 193 | Galan R R. | 1 198 200 |
| Foa | 1 184 | Gamble, J L | 4, 138 144 149 216 219 |
| Fokes, B F | 2, 208 209 | Gans, B | 4, 79 93 97 98 |
| Foles, J P | 1 187 192 193 | Gardiner E. M | 5 21 31 |
| Follis, R. H | 4, 257 259 | Gardner E. | 5 248 264 |
| Forbes, G B | 4, 109 113 127 | Gardner G | 3 10 18 |
| | 135 143 149 | Gardner W U | 1 153 154 160 161 |
| Fo bes, R. M | 4, 120 121 135 | Garrod, O | 4, 292 293 296 |
| Forster R. E. | 4 264 268 | Gatenby J B | 2 86 96 |
| Forwell, G D | 4, 65 73 | Gauer O H | 4 283 284 296 297 |

- Dewar, M. M. 4, 10, 11
 Deyrup, I. 4, 24, 31
 Diamond E. 4, 24, 31
 Dice, L. R. 3, 10, 18
 Dickerson, J. W. T. 4, 217, 219
 Dickie, L. M. 5, 151, 175
 Dieckmann, W. J. 2, 112, 113
 Dietrich H. 5, 60, 69
 Dilley, W. E. 1, 197, 200, 5, 169, 176
 Dinkhauser, F. 5, 63, 69
 Dlouhá, H. 4, 9, 10, 11, 165, 179
 Dobner, K. 1, 133, 137
 Dobson, E. L. 4, 289, 293
 Dodson 3, 185
 Doisy, C. A. 2, 50, 53
 Dole, V. P. 4, 67, 73, 77
 Doljanski, F. 5, 208
 Donohue, D. 4, 46, 56
 Donohue, D. M. 2, 237, 238
 Dorfman, R. I. 1, 126, 130, 134, 137, 4, 90, 93, 187, 195
 Dornhorst, A. C. 2, 234, 238
 Dorst, J. 3, 27, 29
 Douglass, F. M. 1, 156, 161
 Downing, D. F. 1, 193, 200
 Doyle, A. E. 4, 278, 293
 Dreizen, S. 1, 193, 200
 Drescher, A. N. 4, 145, 149
 Droop, M. R. 1, 187, 193
 Drummond, J. K. 3, 107
 D Silva, J. L. 2, 143, 148, 149, 150, 158
 Dublin, L. I. 1, 193, 200, 203, 3, 35, 90, 137, 142
 Dubois, A. B. 4, 264, 268
 Dubois, E. 5, 123, 132
 Duckworth, J. 2, 184, 187, 4, 309
 Duesberg, J. 2, 86, 91, 96
 Duetz, G. H. 3, 83
 Duncan, L. E. 1, 139, 3, 78, 90, 4, 89, 92, 226, 250, 292, 293, 294, 297
 Dunewitz, A. 1, 193, 200
 Dunham, L. J. 1, 151, 158, 160
 Dunn, Th. B. 3, 121, 122, 124
 Dunning, M. F. 4, 46, 56
 Dupret, L. 2, 136, 143
 Dyke, H. B. van 4, 92, 94
 Dymond, J. R. 5, 174
 Dyrenfurth, I. 4, 89, 93, 291, 294
 Eadie, G. S. 2, 234, 238
 Earle, D. P. 4, 271, 295
 Eberlein, W. R. 4, 80, 92
 Economou-Mavrou, C. 4, 218, 219
 Eddy, M. 1, 160
 Edelman, I. S. 4, 36, 47, 38, 109, 113, 260, 295
 Edmonds, S. J. 5, 169, 175
 Edmunds, T. R. 1, 156, 249
 Leg Larson, N. 1, 111, 114, 115, 123, 122, 123
 Eichenberger, L. 4, 119, 125
 Eichna, L. W. 4, 275, 293
 Ladigevis, L. V. 5, 33, 34
 Einstein, A. 2, 227, 231
 Eisenberg, S. 4, 253, 263
 Ek, J. 4, 273, 279, 280, 283, 293, 296
 El Deeb, A. L. A. 5, 232, 234, 241
 Eliasch, H. 4, 273, 279, 280, 283, 293, 296
 Elikin, R. 5, 163, 176
 Elington, J. R. 4, 35, 46, 58, 259, 293, 297
 Elliott, R. H. 2, 120, 125
 Ellis, R. S. 5, 245, 264
 Elmadjian, F. 1, 219, 219, 223, 224, 225, 226, 227, 230, 232, 233, 234, 236
 Elrick, H. 1, 199, 200
 Elsdon Dew, R. 3, 153
 Livchym, C. A. 1, 197, 200, 4, 135, 136
 Ely, R. S. 4, 105, 113
 Emerson, A. L. 1, 10, 14
 Engel, S. L. 4, 92, 93, 237, 239
 Engeler, W. 5, 59, 69
 Engfeldt, B. 2, 162, 172
 Engle, L. T. 1, 151, 160, 2, 60, 66
 Engstrom, W. W. 4, 42, 56
 Entmann, F. V. 2, 36, 37, 54
 Epstein, F. H. 4, 46, 57
 Erickson, D. W. 4, 196, 197, 203
 Ershoff, B. A. 1, 197, 201
 Escher, D. J. W. 4, 277, 280, 295, 297
 Eschmeyer, P. H. 4, 197, 207
 Fassen Moller, L. 3, 134, 142
 Fetheridge, J. 4, 109, 113
 Evan, J. V. 4, 201, 202, 203, 205, 221
 Evans, B. M. 4, 265, 268
 Evans, C. A. 4, 297
 Evans, H. 5, 92, 103
 Evans, H. M. 1, 29, 3, 41, 33
 Evans, W. A. 4, 243, 246
 Evenius, C. 5, 232, 241
 Everett, N. B. 2, 34, 35
 Evermann, B. W. 5, 212, 225
 Ewing, G. 4, 233, 296
 Fahmy 2, 123
 Fahr, H. O. 5, 110, 112
 Failla, A. 5, 239
 Faistat, T. D. 2, 19, 29, 168, 172
 Fairbaird, A. 4, 292, 293, 295
 Falck, A. 3, 132, 139, 143
 Falk, G. 4, 6, 11, 12, 13, 167, 169, 172, 179
 Falcone, J. A. 3, 77, 60
 Farber, S. J. 4, 275, 295
 Fargo, W. C. 1, 164, 201
 Farner, D. S. 5, 9, 101, 102, 103
 Farr, W. 5, 9

CUMULATIVE AUTHOR INDEX

9

| | | | |
|----------------------|------------------------|-----------------|--------------------------|
| Hall, D A | 1 104 | Heady J A | 5 21 31 |
| | 3, 65 66 67 96, 97 | Hebb D O | 3 174 182 |
| 98 100 101 103 5 113 | | Hecht, H R | 4 266 268 |
| Hall, F G | 2, 120 125 | Hechter O | 1 139 4 262 |
| Hall, K. | 4 256 259 | Hediger H | 2, 177 183 |
| Hall, P E. | 4 274 277 297 | Hegsted D M | 1 109 121 122 |
| Haliman, N | 4, 207 202 203 205 | Heidenha n R | 4, 63 73 |
| Halperin M H | 4 279 296 | Heidrunn L V | 1 55 |
| Hamburger J | 4 262 | Helm, A W | 3 163 168 |
| Hamilton, B | 4, 10 11 | Hennebocker P | 4 236 237 259 |
| Hamilton H B | 1 227 236 | Hemangek J | 5, 235 237 242 |
| Hamilton, J A | 4, 242 246 | Helikson J | 1 193 201 |
| Hamilton J B | 1 227 236 | Heller H | 4 6 7 11 12, 12 |
| Hamilton, T S | 4 120 121 131 133 | | 13 13 97 98 114 137 |
| Hamilton, W F | 4, 275 279 295 | | 163 166 167 168 169, |
| Hamilton, W J | 2, 114 115 | | 178, 179 195 396 247 333 |
| | 116 117 155 156 158 | Hellman L M | 2, 111 112, 113 129 |
| | 159 160 | | 132 144 4, 82 85 93 251 |
| Hamlett, G W D | 2 38 40 53 56 | | 239 |
| Hammond J | 1 189 193 | Hems, J | 3 9 18 5, 227 |
| Hancock W | 4, 63 73 | Henly A A | 1 130 137 |
| Hanley T | 4 269 | Henry J P | 4 38 37 283 284 |
| Hanon, F | 4, 217 219 | | 296 297 |
| Hansen E. | 5 59 69 | Henschel A | 4 257 161, 162 |
| Hansen, J D L. | 4 133 135 | Herald E. S | 5, 155 176 |
| Hansen W H | 3, 123 124 | Herbeuval R. | 4 242 246 |
| Hanyu I | 5 151 173 | Herbst, E. J | 1, 197 200 |
| Harrison C R | 5 73 79 | Herkel, W | 2, 151 158 |
| Harris, B A. | 2, 129 132 143 | Herliant, M | 2, 39 40 42 53 |
| Harris, E J | 4 40 31 | Herliuzka A | 2, 33 53 |
| Harris G W | 1 152 160 | Herrington, W C | 5 131 177 |
| Harris, H | 4, 207 203 203 | Hers, H G | 2, 136 143 |
| Harrison, J H | 4 43 37 | Herschmer A | 4 150 |
| Harrison, J L | 5 95 96 102 | Hertug A. T | 1 145 161 2, 110 113 |
| Harrison M F | 1 191 193 | Hertz, R | 1 143 151 160 |
| Harrison, R J | 2 37 34 68, | Hervey G F | 5 227 |
| | 81 83 83 84 85 115 148 | Hervey G R. | 4, 40 57 |
| | 148 149 150 153 156 | Hess A | 3 146 |
| | 158 159 160 199 | Hess, G | 5 233 242 |
| Harrison, T R | 4 283 287 288 296, | Hess, J H | 4, 130 135 |
| | 298 | Hesselberg C. | 2, 80 83 84 |
| Hartman C G | 1 146 160 | Heston W E. | 3 116 121 124 |
| Hartmann W | 5, 59 69 | Heuster K. | 4, 181 195 |
| Harvey G F | 3 9 18 | Hevesy G | 2, 204 209 |
| Hartw g, W | 5 56 57 65 66 67, | Hickey J J | 5, 97 101 102 |
| | 69 70 71 | Hickling, C F | 5, 195 196 |
| Hart, J L | 5, 144 151 155 175 | | 205 207 |
| | 176 | Higgins, G | 4, 36 41 43 57 |
| Hart, J S | 5, 170 175 | Higginson J | 3 110 114 |
| Hass, G M | 1 88 103 | Hidden T | 4 41 56 |
| Hasings | 1 207 | Hie R | 5 151 176 |
| Hasings, A B | 2, 145 143 144 3, | Hil, | 2 127 |
| | 192 4 119 120 131 135 | Hill, A V | 1 71 76 77 78 |
| Hatai, S | 5 248 264 | Hill S | 2, 151 158 |
| Hatcher J D | 4 279 296 | Hilp N A | 2, 60 66 |
| Hatey J | 2, 24 27 | Hill A | 4 272 298 |
| Hathorn M | 3, 104 106 114 | Hilman D | 4 140 141 146 149 |
| Hation, H | 1 10 15 | Hilton J G | 4 243 246 |
| Haugen G E | 2, 130 143 | Hilbert, J | 4, 273 278 279 296 |
| Havighurst, R J | 1 43 48 | Himw ch | 1 51 |
| Hawkins, D P | 4 90 95 | Hines, B E | 4 214 219 |
| Haydak, M H. | 5, 232 236 237 238 | Hungerty D J | 4 35 99 99 |
| | 239 241 242 253 264 | | 101 113, 207 207 226 |
| Hayman J M | 4 271 288 297 | | 226, 247 310 310 |

- Gaunt, R. 4, 193, 194, 195, 296
 Geiser, S. W. 5, 167, 175, 177
 Gele, P. 4, 273, 278, 296
 Gellerstodt, N. 1, 35, 48, 3, 147
 Geilhorn, A. 2, 111, 113, 118, 125, 148, 153
 Genest, J. 4, 277, 296
 Geoghegan, H. 4, 24, 31, 35
 Gérard, P. 2, 39, 40, 42, 53, 56
 Gerking, S. D. 5, 18, 79, 171, 175, 179, 180, 181, 183, 207, 209, 210, 211, 228, 229, 230, 265, 284, 289
 Gerner, K. 5, 63, 69
 Gerritsen, T. 3, 110, 114
 Gianferrari, L. 3, 137, 142
 Giardini, A. 4, 73
 Gibson, J. G. 4, 243, 246
 Gibson, J. R. 5, 29, 31
 Gilbert, C. 3, 126
 Gilbert, C. S. 5, 243
 Gilbert, J. C. 3, 160, 169
 Gilligan, D. R. 1, 90, 103
 Gilman, A. 4, 37, 57
 Gilman, J. 3, 20, 26, 104, 105, 106, 107, 108, 109, 114, 126, 189
 Gilmán, T. 3, 33, 36, 48, 49, 70, 70, 72, 96, 100, 104, 104, 103, 106, 107, 108, 109, 114, 126, 145, 146, 188, 189, 190
 Ginsburg, J. 2, 143, 158
 Ginsburg, M. 4, 46, 57
 Girard, A. 1, 129, 137
 Giroud, A. 2, 163, 172
 Giroud, C. J. 4, 293, 294
 Glass, B. 3, 136, 142
 Godden, W. 4, 309
 Godet, R. 2, 16, 17
 Godwin, H. 2, 206, 209
 Gömöri, P. 4, 284, 286, 296
 Gofman, 1, 89
 Goldblatt, H. 4, 253, 258, 259
 Golden, J. B. 1, 143, 153, 160
 Goldfarb, N. 3, 171, 182
 Goldhamer, H. 1, 41, 43
 Goldner, F. 4, 38, 40, 43, 44, 57
 Goldring, W. 4, 280, 246
 Goldstein, K. 3, 180, 182
 Gómez, P. 1, 195, 200
 Gompertz, D. 5, 2, 15, 72, 79, 802, 311
 Gonse, P. 2, 21, 26
 Gontaraki, H. 5, 232, 241
 Goodbody, M. F. 4, 243, 246
 Goodman, L. 1, 151, 160
 Gordon, 3, 138
 Gordon, E. B. 4, 49, 56
 Gordon, E. E. 2, 142, 143, 144
 Gordon, E. S. 4, 292, 296
 Gordon, G. L. 4, 38, 40, 43, 44, 57
 Gordon, J. 4, 226, 237, 239
 Gordon, J. E. 5, 21, 31
 Gottlieb, E. 5, 149, 175
 Gotzche, H. 4, 41, 56
 Gould, R. G. 2, 217, 232
 Gowenlock, A. H. 4, 60, 193, 195
 Graber, 4, 151
 Graham, I. 3, 98, 100
 Grainger, E. H. 5, 147, 153, 175
 Gram, M. R. 1, 122, 123
 Granick, S. 2, 238
 Gray, M. J. 4, 89, 93
 Greaves, M. S. 4, 263, 263
 Green, C. V. 3, 9, 18
 Green, H. H. 4, 200, 203
 Green, R. G. 5, 297
 Green, S. H. 2, 32, 33, 53
 Greenberg, D. M. 4, 307, 307, 308, 309
 Greene, R. 4, 84, 93
 Greene, R. R. 2, 3, 12, 17
 Greenfield, A. D. M. 2, 120, 121, 123
 Greenwood, M. 5, 311
 Groppe, R. O. 2, 63, 66
 Gregory, F. G. 2, 204, 207, 209
 Gresson, R. A. R. 2, 86, 96
 Grubetz, D. 4, 143, 149
 Grew, S. 3, 166, 169
 Griffin, G. E. 4, 109, 113
 Griffith, L. 4, 109, 113
 Griffiths, J. T. 5, 277, 281
 Groot, A. P. de 5, 235, 236, 237, 238, 241
 Grosch, D. S. 5, 215, 264
 Gross, F. 1, 242
 Gross, J. 3, 43
 Grossman, M. I. 1, 191, 193
 Grossman, R. 4, 280, 295
 Grosz, S. 2, 179, 183
 Gruber, G. B. 2, 181, 183
 Grüneberg, H. 1, 238, 3, 118, 124, 5, 19, 20, 79, 80, 283
 Grueninger, R. M. 1, 193, 201
 Gruenwald, P. 2, 16, 17
 Guild, W. R. 4, 43, 56, 57
 Guilford, J. P. 1, 40, 48
 Gumbel, E. J. 5, 117, 132, 134
 Gunter, G. 5, 167, 175
 Guzmán, M. A. 1, 193, 200
 Haddow, A. 3, 68
 Hagel, L. 5, 59, 69
 Hagerman, D. D. 2, 142, 144
 Hahn, P. 4, 165, 179
 Hahn, P. F. 2, 236, 238
 Hafler, I. 5, 196, 208, 218, 225, 226
 Haigh, L. D. 4, 131, 133
 Hain, A. M. 2, 162, 172
 Halberstaedter, L. 2, 46, 51
 Hald, A. 5, 120, 131
 Haldane, J. B. S. 1, 10, 11, 238, 3, 5, 12, 18, 5, 33, 54
 Haldane, J. S. 4, 65, 73
 Haley, H. B. 4, 109, 113

| | | | |
|--------------------|-------------------------------|-------------------|-----------------------------------|
| Jones, E. C. | 5, 271, 31 | Kety, S. S. | 3, 147, 4, 286, 296 |
| Jones, E. R. | 4, 130, 135 | Keys, A. | 1, 89, 7, 3, 75, 91, 4, |
| Jones, H. E. | 3, 160, 168, 171, 182 | | 157, 161, 162 |
| | 186 | Kidd, F. | 2, 206, 209 |
| Jones, H. S. | 4, 64, 73 | Killmann, S. A. | 4, 63, 65, 68, 73 |
| Jones, J. W. | 5, 153, 156, 176 | Kilpatrick, J. A. | 4, 266, 268 |
| Jones, R. V. H. | 4, 54, 57 | Kinball, G. C. | 4, 233, 237, 239 |
| Jordan, D. S. | 5, 212, 2, 6 | King, G. | 5, 10 |
| Josephson, B. | 4, 279, 280, 293 | King, H. D. | 3, 20, 29 |
| Josimovich, J. B. | 2, 23, 26 | King, J. O. L. | 5, 56 |
| Jost, A. | 2, 3, 11, 12, 13, 13, 14, 15 | King, J. W. B. | 4, 202, 203, 205 |
| | 16, 17, 18, 18, 19, 20, 21 | Kinney, T. D. | 3, 189 |
| | 23, 24, 26, 27, 27, 28, 29 | Kirk, E. | 1, 227, 236 |
| | 30, 34, 116, 126, 127, 146 | Kirk, J. E. | 1, 69, 69, 75, 76, 76, 77, 78, 79 |
| | 167, 172, 173, 1, 4, 175 | Kittsteiner, C. | 4, 63, 73 |
| | 252 | Klaar, J. | 2, 197, 198, 199, 200 |
| Judson, W. E. | 4, 279, 296 | Klaber | 3, 139 |
| June, F. C. | 5, 193, 208 | Klauber, L. M. | 3, 21, 29 |
| | | Klavins, J. | 3, 189 |
| Kadić, M. | 5, 43, 54 | Kleeman, C. R. | 4, 46, 57 |
| Kagan, B. M. | 4, 130, 135 | Klein | 2, 127 |
| Kahlenberg, O. J. | 4, 127, 135 | Klein, M. | 1, 154, 160 |
| Kalabouh, N. I. | 5, 96, 102 | Kleinman, A. | 4, 133, 135 |
| Kallas, H. | 1, 144, 160 | Kleinzel, A. | 4, 33, 287, 288, 295 |
| Kallmann, F. J. | 1, 42, 48, 3, 37, 101 | Klopfert, H. W. | 3, 134, 136, 143 |
| | 131, 132, 133, 137, 139 | Klug, H. L. | 4, 133, 135 |
| | 142, 143, 143, 144, 145 | Kluyver, H. N. | 5, 99, 102 |
| | 146, 147, 148, 173, 182 | Knob, E. | 2, 166, 172 |
| Kalter, H. | 2, 168, 172 | Knowles, H. C. | 4, 36, 57 |
| Kaplan, S. A. | 4, 287, 296 | Knox, G. | 5, 21, 31 |
| Karnovsky, M. L. | 2, 141, 143 | Koch, A. | 5, 236, 238, 242 |
| Karvonen, M. J. | 4, 74, 76, 199, 201 | Kocher, V. | 5, 237, 242 |
| | 202, 203, 203, 206, 207 | Koczorek, K. R. | 4, 280, 292 |
| | 208, 221, 316 | | 293, 298 |
| Karvink, G. S. | 5, 186, 208 | Kochler, A. | 5, 232, 242 |
| Kasala, E. | 4, 74 | Kohler, M. | 4, 292, 298 |
| Katersky, E. M. | 1, 90, 103 | Kong, K. | 5, 61, 62, 69 |
| Kattus, A. | 4, 277, 296 | Kottay, E. | 4, 284, 286, 296 |
| Katz, J. | 4, 257, 259, 261 | Kond, A. | 3, 189 |
| Katz, M. | 5, 196, 197, 208 | Konopaska | 5, 67, 69 |
| Kaufman, N. | 3, 189 | Koon, G. T. | 4, 301, 308 |
| Kaufman, E. F. | 2, 228, 231 | Kopce, S. | 1, 197, 200, 3, 25, 29 |
| Kay, H. | 1, 213, 3, 162, 169, 182, 183 | Korenchevsky, V. | 4, 256, 259 |
| Keech, M. K. | 3, 97, 100, 103 | Kosteritz, N. | 2, 166, 172 |
| Keey, R. B. | 3, 10, 18 | Kovach, A. | 4, 284, 286, 296 |
| Kellner, G. | 2, 36, 42, 43, 53 | Kovach, A. G. B. | 4, 45, 57, 284, 286, 296 |
| Kellogg, V. L. | 1, 196, 200 | Kovach, I. | 4, 157, 161 |
| Kennedy, G. C. | 1, 189, 193 | Kowalewski, K. | 1, 227, 236 |
| | 4, 136, 136, 137, 150, 164 | Kracke, R. R. | 2, 172, 173 |
| | 197, 2, 6, 227, 250, 251 | Kratky, E. | 5, 232, 236, 242 |
| | 253, 254, 257, 259, 260, | Krause, C. | 5, 110, 112 |
| | 261, 262, 263, 313, 314 | Krecek, J. | 4, 9, 10, 11, 113 |
| | 317 | | 165, 179, 195, 196, 316 |
| Kennedy, W. A. | 5, 145, 151, 176 | Křečková, J. | 4, 9, 10, 11, 165, 179 |
| Kerpel-Fronius, E. | 4, 39, 57, 96 | Krogh, A. | 1, 77, 4, 75 |
| | 105, 173, 154, 155, 157 | Krohn, P. L. | 1, 30, 139, 141, 156 |
| | 161, 162 | | 160, 162, 172, 203, 242, |
| Kerr, S. E. | 4, 202, 203 | | 245, 2, 57, 65, 67, 84, 211, |
| Kerrigan, G. A. | 4, 139, 140, 141, 146 | | 239, 240, 243, 249, 250 |
| | 147, 149 | | 252, 3, 123, 124, 125, 126 |
| Kershaw, W. E. | 5, 56, 56, 70, 105 | | 127, 5, 271, 281 |
| | 114, 245, 267, 285 | Krues, O. R. | 4, 245, 246 |
| Keston, A. S. | 2, 206, 209 | Krumholz, L. A. | 5, 171, 176 |
| Keszler, H. | 4, 297, 296 | | 187, 188, 208 |

| | | | |
|--------------------|---|----------------|---|
| Hinshelwood C. | 3, 5 18 | Hunter W R. | 5, 179 |
| Hinton, H. E. | 5 34 112, 243, 245,
246, 284 | Hurley T H | 2, 233 239 |
| Hinton, S. | 5 191 217 219, 225 | Hurst, H | 3, 10, 18 |
| Hippocrates | 2, 129 | Hurst, J G | 1, 155 161 |
| Hisaw F L. | 1 143, 151 160 | Huseby R. A. | 1, 155, 160 |
| Hitchcock, M W S | 2, 122 125 | Huxley J | 5, 104 |
| Hoagland, H | 1, 219 223 224 225
226, 227 230 232 233 | Hyett, A R. | 2, 153 159 |
| Hobbs, G E. | 1 223 232 236 | Hynes, N H B. | 5, 153 156 176 |
| Hobson, W | 3, 94 100 | Hyttén P E. | 5, 33 |
| Hodge, C F | 5 243 264 | Ickowicz, M | 2, 46, 53 |
| Hoezel, F | 1 197 199 206 | Ikkos, D | 4, 109 113 |
| Hoffman, F G | 2, 39 54 | Ingle, D J | 4, 257 259 260 |
| Hoffman, H | 5, 237 243 | Ingle, L. | 1 197 200 3, 24 29 |
| Hoffman, J | 1, 153 160 | Ingram D L. | 2, 35 44 53 |
| Hoffman K. | 1 153 161 | Innes, L R. | 2, 166, 172 |
| Hogreve, P | 5, 64 65 69 | Inukai T | 5, 284 284 |
| Holland B. C | 4, 51 57 | Iob, L V | 4, 130, 135 |
| Hollander | 2, 251 | Irving, J T | 1, 110, 123 |
| Hollander W | 4, 279 296 | Irwin, J O | 5, 37 54 |
| Holliday M A | 4, 129 135 | Iseri L T | 4, 289 296 |
| Holmes, E. G | 4, 130 135 | Ish, B. | 1, 175 185 |
| Holmes, S. J | 5, 21 31 | Ispov A P | 5, 33 54 |
| Holmgren A. | 4, 279 280 293 | Ito T | 2, 189 199 |
| Holt, S. J | 5, 86 134 142, 149 151
153 158 167 175 176
178 179 209 210 226,
227 228, 229 246, 290 | Itoh, S. | 4, 24 32 |
| Homma H | 2, 185 191 192 199 | Ivlev V S | 3, 186 207 208 |
| Honzo, H | 4, 291 296 | Ivy A C | 2, 12 |
| Hoogendoorn, D | 5, 21 31 | Iwashige, K. | 2, 189 191 199 |
| Hooker C W | 2, 91 96 | Izzo M J | 2, 236 239 |
| Hope, J M | 1 219 223 224 225
226 227 232 233 236 | Jackson, B H | 5, 89 |
| Hopwood H H | 1 198 201 | Jackson H | 1, 54 |
| Horn, G | 2, 189 199 | Jackson L | 1 122 123 |
| Howell, T H | 1 18 23 | Jackson W P U | 2, 167 172 |
| Hoy P A | 4 3 4 5 6 9 11 | Jacob H | 3, 134 142 |
| Huant, E. | 2, 167 172 | Jacob, M | 4, 252 259 |
| Hubble, D | 4, 78 93 | Jacobsohn, D | 1 152 160 |
| Hubba, C L. | 5 146 155 176 | Jacquot, R | 2, 24 27 |
| Hudson, P | 1, 136 137 | Jaczewski, Z. | 2, 181 182 183 |
| Huggess, A. St G | 2, 21 29 56
58 84 116, 117 119
120 121 123 125 126
127 144 145 146, 159
160 174 175 186, 200,
201 210, 214 240, 242,
243 246, 247 251 252 | Jaeger L M | 3, 3, 29 |
| Hughes, A. | 2, 251 | Jalavisto Ecva | 3, 137, 142 5, 16,
17 21 23 31 31 32,
31 81 113 266 |
| Hughes, J S. | 4, 200 205 | James, A H | 4, 109 113 |
| Hughes Jones, N C. | 2, 234, 235
235 4, 263 268 | James, D W | 3, 70 |
| Hugin, F | 3, 63 64 67 | James, W | 1 43 |
| Hull, T Z. | 4, 131 135 | James, W O | 2, 203 209 |
| Hultquist, O T | 2, 162 172 | Jelinek J | 4, 165 |
| Hummel, K P | 1 156, 160 | Jenkins, R | 5, 168 178 |
| Humphries, E M | 2, 34 32 53 | Jenn nga | 2, 252 |
| Hungerland, H | 4, 212 219 | Jenson, R L. | 4, 2 2 |
| Hunt, J N | 4, 210, 219 | Jepson, R P | 4, 150 |
| | | Jeter, M A. | 2, 148 159 |
| | | Jewell, P A. | 4, 37 57 |
| | | Johansson, A S | 5, 53 |
| | | John, M | 5, 217 222 |
| | | Johansen, S O | 1, 69 75, 76 |
| | | Johnson, B. H. | 4, 187 193 280 293
294 297 |
| | | Johnson, L C | 1 143 161 |
| | | Johnston, M E. | 4, 49 58 |
| | | Jolliffe N. | 1 199 200 |
| | | Jolly W A. | 2, 33 54 |
| | | Jones, A R. | 2, 225 |

CUMULATIVE AUTHOR INDEX

11

| | | | |
|--------------------|---|------------------|--|
| Jones, E. C. | 5, 271 281 | Kelly S. S. | 3 147 4 286 296 |
| Jones, E. R. | 4, 130 135 | Keys, A. | 1 89 207 3, 75 91 4, 157 161 162 |
| Jones, H. E. | 3 160 168 171 182 186 | Kidd F. | 2, 206 209 |
| Jones, H. S. | 4 64 73 | Kilmann S. A. | 4, 63 65 68 73 |
| Jones, J. W. | 5 153 156 176 | Kilpatrick J. A. | 4 266 268 |
| Jones, R. V. H. | 4, 54 57 | Kimbrell G. C. | 4, 253, 257 259 |
| Jordan, D. S. | 5 212 226 | King, G. | 5 10 |
| Josephson B. | 4, 279 280 293 | King, H. D. | 3 20 29 |
| Jos mov ch, J. B. | 2, 23 26 | King, J. O. L. | 5 56 |
| Jost, A. | 2, 3 11 12 13 14 15 16 17 18 19 20, 21 23 24 6 27 27 28 29 30, 84 116 126 127 146 167 172 173 174 175 252 | King, J. W. B. | 4 202, 203 205 |
| Judson W. E. | 4, 279 296 | Kinney, T. D. | 3 189 |
| June, F. C. | 5, 193 208 | Kirk, J. E. | 1, 227 236 |
| Kadić, M. | 5 43 54 | Kirk J. E. | 1 69 69 73 76 76, 77 78, 79 |
| Kagan B. M. | 4, 130 135 | K. is c ner C. | 4, 63 73 |
| Kahlebe g, O. J. | 4 127 135 | Klat J. | 2, 197 198 199 200 |
| Ka abouchov N. I. | 5 96 102 | Klaber | 3 139 |
| Kallas, H. | 1 144 160 | Klaber L. M. | 3 21 29 |
| Kallmann F. J. | 1 42 48 3 37 107 131 132 133 137 139 142 143 143 144 145 146 147 148 173, 182 | Kla ins J. | 3 189 |
| Kalter H. | 2, 168 172 | Kleeman C. R. | 4 46 57 |
| Kap an, S. A. | 4, 287 296 | Klein | 2, 127 |
| Karnovsky M. L. | 2, 141 143 | Klein M. | 1 154 160 |
| Karvonen M. J. | 4 74 76 199 207 202 203 205 206 207 08 221 316 | Kleiman, A. | 4 133 135 |
| Karzon G. S. | 5 186 208 | Klempner A. | 4 33 287 288 295 |
| Kassia, E. | 4 74 | Klopper H. W. | 3 134 136 143 |
| Karsky E. M. | 1 90, 103 | Klug, H. L. | 4 133 135 |
| Kasut, A. | 4 277 296 | Klout er H. N. | 5 99 102 |
| Katz, J. | 4 257 259 261 | Knob l E. | 2, 166 172 |
| Katz, M. | 5 196 197 208 | Knawles, H. C. | 4 36 57 |
| Kaufman N. | 3 189 | Knox, G. | 5 21 31 |
| Kauzman E. F. | 2 228 231 | Koch A. | 5, 236 238 242 |
| Kay H. | 1 213 3 162 169 182 183 | Kocher V. | 5 237 242 |
| Keech M. K. | 3 97 100 103 | Kolczorek K. R. | 4, 280, 292 293 298 |
| Ke ley R. B. | 3 10 18 | Koehler A. | 5 232 242 |
| Ke ner G. | 1, 36 42 43 53 | Koh er M. | 4 292 298 |
| Ke ogg, V. L. | 1 196 200 | Kong, K. | 5 61 62 69 |
| Kennedy G. C. | 1 189 193 4 136, 136 137 150 164 197 226 227 250 251 253 254 257 259 260 61 262, 263 313 314 317 | Koltay L. | 4, 284 286 296 |
| Kennedy W. A. | 5 145 151 176 | Kond A. | 3 189 |
| Kerpel Fronius, E. | 4, 39 57 96 105 113 154 155 157 161 162 | Konopinska | 5 67 69 |
| Kerr S. E. | 4, 202 205 | Kong, T. | 4 301 308 |
| Kerrigan, G. A. | 4 139 140 141 146 147 149 | Kopeck, S. | 1 197 200 3 25 29 |
| Kershaw W. E. | 5, 56 56 70 105, 114 245 267 285 | Korenchevsky V. | 4 256 259 |
| Keston, A. S. | 2, 206 209 | Kosterlitz, N. | 2, 166 172 |
| Kezle H. | 4, 291 296 | Ko sch A. | 4 284, 286 296 |
| | | Kovách A. G. B. | 4 45 57 284 286 296 |
| | | Kovách I. | 4 157 161 |
| | | Kowalewski K. | 1 227 236 |
| | | Kracke R. R. | 2, 112 113 |
| | | Kratky E. | 5 232 236 242 |
| | | Krause C. | 5 110 112 |
| | | Křeček J. | 4 9 10 11 113 |
| | | Křečková J. | 163 179 193 196, 316 |
| | | Krogh A. | 4 9 10, 11 165 179 |
| | | Krohn P. L. | 1 77 4 75 |
| | | | 1, 30, 139 141 156 |
| | | | 160 162 172, 203 242, 245 2, 57 65 67 84 211 239 240 243 249 250 252 3 123 124 125 126 127 5 2 1 281 |
| | | Krues O. R. | 4, 245 246 |
| | | Krumholz, L. A. | 5, 171 176 187 188 208 |

- Kruse, H. D. 4, 301, 308
 Kuechle, M. E. 1, 198, 201
 Kullen, A. 5, 237, 241
 Kuhn, W. 5, 240, 242
 Kun, K. 4, 161, 162
 Kuno, Y. 4, 64, 73
 Kurzrok, R. 1, 145, 160
 Kuznetsova, G. 5, 53, 54

 Lacasse, A. 2, 34, 46, 53
 Lack, D. 1, 4, 15, 5, 97, 101, 102, 104
 Ladman, A. J. 2, 23, 26
 Lambdin, E. 4, 46, 57
 Lamont, N. 3, 105, 133
 Lanciano, G. 1, 199, 200
 Landau, B. R. 2, 141, 143
 Landowne, M. 1, 66, 3, 33, 35, 36, 46, 47, 69, 69, 73, 75, 80, 84, 88, 89, 90, 91, 94, 129, 4, 235, 236, 246
 Lane, C. E. 1, 152, 160, 2, 63, 66
 Lane-Clayton, J. E. 2, 36, 37, 39, 53
 Lang, C. A. 3, 79, 91
 Langley, J. N. 4, 63, 73
 Langmaid, C. 4, 44
 Langstroth, G. O. 4, 64, 65, 73
 Lansing, A. I. 1, 25, 26, 27, 30, 50, 51, 55, 78, 88, 91, 99, 103, 104, 105, 106, 107, 108, 148, 160, 203, 206, 241, 242, 243, 244, 2, 109, 113, 247, 3, 97, 98, 100, 102, 5, 259, 264
 Laragh, J. H. 4, 53, 57, 292, 293, 296
 Lardy, H. A. 2, 203, 209
 Larkin, P. A. 5, 182, 208
 Larsen, C. D. 3, 121, 124
 Larsen, E. L. 4, 95
 Lasch, W. 4, 97
 Laser, H. 4, 218, 219
 Lasso, D. 1, 110, 122, 123
 Laursen, T. J. S. 1, 69
 Lavoisier, M. M. J. 5, 243, 245
 Law, L. W. 1, 147, 160
 Lawson, H. D. 1, 141, 160
 Lea, E. 5, 145, 149, 176
 Leaf, A. 4, 42, 46, 57, 141
 Leavenworth, C. S. 2, 204, 210
 Leblond, C. P. 2, 36, 56
 Ledue, L. H. 2, 251
 Lee, S. van der 3, 117, 121
 Leeson, P. M. 4, 56
 Lehman, H. 1, 39, 40, 43, 51
 Leitch, I. 1, 196, 199
 Leiter, L. 4, 277, 280, 295, 297
 Lell, W. A. 2, 109, 113
 Le Magnen, J. 3, 129
 Le Marquand, H. S. 1, 197, 200
 Lenégre, J. 4, 273, 278, 296
 Lenhossek, M. 2, 64, 66
 Leonard, J. A. 1, 211, 213
 Leppinen, V. 4, 200, 202, 203, 205
 Lesher, S. 5, 60
 Leslie, P. H. 3, 10, 13, 5, 266
 Leutscher, J. A. 4, 264
 Leizer, J. D. 2, 102
 Leverton, R. M. 1, 122, 123
 Levin, M. D. 5, 232, 236, 242
 Levine, A. D. 4, 258
 Levine, J. 4, 228
 Levinson, Z. H. 5, 253, 259, 264
 Lewin, W. 4, 35, 41, 43, 57
 Lewis 2, 103
 Lewis, A. J. 1, 32, 49, 50, 51, 52, 138, 214, 218, 238, 246, 3, 143, 144, 146, 147, 185
 Lewis, C. S. 4, 266, 268
 Lewis, G. T. 4, 127, 134
 Lewis, H. B. 1, 94, 103
 Lewis, K. 1, 33, 43
 Lewis, W. H. 4, 242, 244, 246, 248
 Li 2, 174
 Li, C. H. 1, 29
 Li, M. H. 1, 154, 160
 Liber, K. E. 2, 109, 113
 Liddle, G. W. 4, 89, 92, 200, 292, 293, 294, 297
 Lieb, C. W. 4, 262
 Lieberman, H. M. 5, 250, 251, 255, 256, 257, 258, 260, 264
 Liebman, A. 4, 42, 56
 Liener, I. I. 1, 192, 193
 Light, A. F. 4, 120, 121, 123, 131, 135
 Lightbody, H. D. 4, 133, 135
 Lilly, D. M. 1, 187, 193
 Lindan, G. 2, 112, 113
 Lindauer, M. 4, 235, 242
 Linderstrom Lang, K. 2, 204, 209
 Lindgren, A. 3, 134, 143
 Lindop, Patricia J. 3, 52, 59, 4, 113, 136, 138, 141
 Lippi, B. 4, 242, 248
 Lipshutz, A. 1, 191, 160, 2, 34, 53
 Little, C. G. 1, 156, 160
 Liu, C. H. 1, 110, 122
 Ljunggren, H. 4, 109, 113
 Llaurado, J. G. 4, 291, 297
 Lloyd, C. W. 4, 191, 195
 Lobitz, W. C. 2, 191, 192, 194, 199
 Locke, W. 4, 64, 73
 Lochhead, J. 2, 21, 27, 122, 125
 Loeb, J. 3, 24, 29
 Loeb, L. 1, 146, 157, 159, 160, 2, 41, 54, 54, 55, 69, 70, 71, 71, 80, 81, 84, 161, 172, 2, 164, 197, 199
 Loewhaake, H. 2, 129, 143
 Loewer, H. 2, 129, 143
 Logan, M. A. 1, 91, 103
 Logothetopoulos, J. 4, 241, 248
 Lombardo, A. J. 1, 164, 241
 Lombardo, T. A. 4, 241, 248
 Long, C. N. H. 4, 42, 91
 Longley, L. P. 4, 271, 274, 277
 Lorenz, L. 4, 64

| | | | |
|------------------------|--|----------------|------------------------------|
| Large, I | 3 32 33 36, 37 72, 147
148 170 170 182 183
184 185 186 189 | McGee, L. E. | 3, 52 59 |
| Lotka, A. | 3 137 142 | McGregor E. A. | 5 192 208 |
| Lotmar M | 5, 232 233 234 242 | McGregor J H | 2, 87 96 |
| Louti, J F | 2, 221 232 236, 238 | McHugh T | 5 103 |
| Loucaux, J | 5 236 242 | McIlroy M B. | 1 67 65 |
| Loelock, J E. | 1 163 164 165 | McIntosh, B J | 4 24 31 |
| 168 169 2, 215 217 218 | | MacIntyre, I | 4, 115 |
| 221 224 232 240 241 | | McKeown, T | 5 29 31 |
| 242 243 | | Mackintosh J | 5 21 31 |
| Lowry O H. | 1 90 103 3 192 | MacLaren A. | 3 7 18 |
| 4 120 131 135 | | MacMahon L. | 5 21 31 |
| Lwall, A | 1 110 123 | McMas er P D | 4 29 32 |
| Luck, J M | 4, 132 135 | McMurray J | 4 102 |
| Ludemann, H | 4, 51 56 | McMurray J D | 4 102 106,
103 113 |
| Luette, R. W | 5, 237 243 | MacPhee G | 4 90 93 |
| Luetscher J A | 4 280, 292 293 297 | McRae, D R. | 4 64 63 73 |
| Lutz, R. | 4 109 113 | Maar A | 5, 191 208 |
| Lundberg, A. | 4 69 70 73 76 | Mach, R. S | 4, 292 293 |
| Lundeen E. | 4 130 135 | | 295 297 |
| Lutwak Mann, C | 4 218 219 | Mackler B | 4 40 57 |
| Lutz, R. | 1 122 123 | Macy I G | 4 143 149 |
| Lwoff, A. | 3 46 | Madden, S C | 4 132 133 135 |
| MacArthur J W | 3 24 29 4,
141 149 | Maddock W G | 4 39 57 |
| McCall J T | 2, 148 159 | Magend e | 1 174 |
| McCance, R. A | 1 67 76 77 | Maggion G | 1, 199 200 |
| 103 186, 186 193 197 | | Magnus, I C. | 4 102 106 108 113 |
| 200 203 205 207 3 192 | | Mahler R. F | 4 193 195 |
| 4 1 6 11 13 38 40 41 | | Mahoney J J | 2, 14 15 17 |
| 44 56 57 59 76 95 96 | | Maizels, M | 4 199 205 |
| 96 97, 100 115 120 121 | | Makeham W M | 5 2 4 15,
302 321 |
| 128 136 137 138 150 | | Ma amud N | 3 134 143 |
| 157 160, 162 162, 180, | | Ma erba, G | 4, 242 246 |
| 195 197 199 203 205 | | Malm, O J | 3 109 111 115 120 |
| 207 208 209 211 212 | | | 122 123 |
| 214 215 217 218 219 | | Mamby A R | 4 42 46 57 |
| 222 222, 223 257 259 | | Manca P V | 2, 191 192 199 |
| 262 263 269 298 305 | | Manciaux, M | 4 242 246 |
| 306, 308 309 310 315 | | Mancin R. E | 2, 86 96 |
| MacCarty C S | 4 41 56 | Mandel L | 4, 252 259 |
| Macaskill E H | 4 200 205 | Mandel, P | 4 252 259 |
| Macaulay D | 4 46 57 | Mandelstam J | 3 108 114 |
| McCay C M | 1 27 29 30 122 | Mandi, A M | 1 144 160 2, 32 33 |
| 123 124 125 173 174 | | | 34 35 49 50 51 53 |
| 181 185 188 189 193 | | | 54 60 66 3 127 4,
251 259 |
| 194 197 200 04 206 243 | | Manery J F | 4 106 112 |
| 2, 248 3 8 18 25 29 | | Mangel, M | 1 122 123 |
| 5, 169 176 251 252 253 | | Mannes A | 5 59 60 69 |
| 264 265 268 | | Mantz, F R. | 4 109 113 |
| McCullum, E. V | 4 224 | Marcus, S | 4 187 193 |
| McCormack J I | 4, 24 31 35 | Marden W G R | 1 143 160 |
| McCracken F D | 5 157 175 | Marescaux I | 2, 36 37 38 39 41 |
| McCroly W W | 4, 46 57 | | 42 46 47 53 62 66 |
| MacDonald, A. M. | 4 301 307 | Margetta A R. | 5 151 176 |
| | 308 309 | Markee J E. | 1 152 160 |
| McDonald R K. | 1 220 236 4 | Ma la, H | 3 85 90 |
| 231 233 235 237 246 | | Ma is I N | 4, 301 |
| | 247 | Marlow H | 5 63 69 |
| M Fadyean J | 5, 50 54 | Marmer I L | 4 126 136 |
| McFarland R. A | 3 133 143 | Marmorston, J | 4 257 259 261 |
| McGaughy R. S | 4 289 296 | Marr J C | 5 153 176 |
| | | Marsden, J L. | 3, 56 |

- Kruse, H. D. 4, 301, 308
 Kuechle, M. E. 1, 198, 201
 Kuiken, A. 5, 237, 243
 Kuhn, W. 5, 240, 242
 Kun, K. 4, 161, 162
 Kuno, Y. 4, 64, 73
 Kurzrok, R. 1, 145, 160
 Kuznetsova, G. 5, 53, 54

 Lacassagne, A. 2, 34, 46, 53
 Lack, D. 1, 4, 15, 5, 97, 101, 102, 104
 Ladman, A. J. 2, 23, 26
 Lambdin, E. 4, 46, 57
 Lamont, N. 3, 105, 183
 Lanciano, G. 1, 199, 200
 Landau, B. R. 2, 141, 143
 Landowne, M. 1, 66, 3, 33, 35, 36, 46, 47, 69, 69, 73, 75, 80, 84, 88, 89, 90, 91, 94, 129, 4, 235, 238, 246
 Lane, C. E. 1, 152, 160, 2, 63, 66
 Lane-Clayton, J. E. 2, 36, 37, 39, 53
 Lang, C. A. 3, 79, 91
 Langley, J. N. 4, 63, 73
 Langmaid, C. 4, 44
 Langstroth, G. O. 4, 64, 65, 73
 Lansing, A. I. 1, 25, 26, 27, 30, 50, 51, 55, 78, 88, 91, 99, 103, 104, 105, 106, 107, 108, 143, 160, 203, 206, 241, 242, 243, 244, 2, 109, 113, 247, 3, 97, 98, 100, 102, 5, 259, 264
 Laragh, J. H. 4, 53, 57, 292, 293, 296
 Lardy, H. A. 2, 208, 209
 Larkin, P. A. 5, 182, 208
 Larsen, C. D. 3, 121, 124
 Larsen, E. E. 4, 93
 Lasch, W. 4, 97
 Laser, H. 4, 218, 219
 Laszio, D. 1, 110, 122, 123
 Laurien, T. J. S. 1, 69
 Lavoisier, M. M. J. 5, 243, 283
 Law, L. W. 1, 147, 160
 Lawson, H. D. 1, 143, 160
 Lea, L. 5, 143, 149, 176
 Leaf, A. 4, 42, 46, 57, 145
 Leavenworth, C. S. 2, 201, 210
 Leblond, C. P. 2, 36, 66
 Ledue, E. H. 2, 251
 Lee, S. van der 3, 117, 123
 Leeson, P. M. 4, 36
 Lehman, H. 1, 39, 40, 48, 51
 Leitch, I. 1, 146, 199
 Lester, L. 4, 277, 283, 291, 297
 Lell, W. A. 2, 109, 113
 Le Magnien, J. 3, 129
 Le Marquand, H. S. 1, 197, 200
 Lefèvre, J. 4, 273, 273, 296
 Lenhousck, M. 2, 86, 96
 Leonard, J. A. 1, 211, 213
 Leppänen, V. 4, 200, 202, 203, 203
 Lesher, S. 5, 83
 Leslie, P. H. 3, 10, 18, 5, 298
 Leutscher, J. A. 4, 294
 Lever, J. D. 2, 103
 Leverton, R. M. 1, 122, 123
 Levin, M. D. 5, 232, 238, 242
 Levine, A. D. 4, 229
 Levine, J. 4, 229
 Levinson, Z. H. 5, 255, 259, 264
 Lewin, W. 4, 36, 41, 43, 57
 Lewis 2, 103
 Lewis, A. J. 1, 32, 49, 50, 51, 52, 138, 214, 218, 238, 246, 3, 143, 144, 146, 147, 185
 Lewis, C. S. 4, 266, 268
 Lewis, G. T. 4, 127, 134
 Lewis, H. B. 1, 94, 103
 Lewis, K. 1, 33, 48
 Lewis, W. H. 4, 242, 244, 246, 248
 Li 2, 174
 Li, C. H. 1, 29
 Li, M. H. 1, 154, 160
 Liber, K. E. 2, 109, 113
 Liddle, G. W. 4, 89, 92, 200, 293, 293, 294, 297
 Lieb, C. W. 4, 262
 Lieberman, H. M. 5, 250, 251, 255, 256, 257, 258, 260, 264
 Liebman, A. 4, 42, 56
 Liener, I. E. 1, 192, 193
 Light, A. E. 4, 120, 121, 123, 131, 133
 Lightbody, H. D. 4, 133, 133
 Lilly, D. M. 1, 187, 193
 Lindan, O. 2, 112, 113
 Lindauer, M. 5, 233, 242
 Linderstrom Lang, K. 2, 204, 209
 Lindgren, A. 3, 134, 143
 Lindop, Patricia J. 3, 52, 59, 5, 113, 136, 138, 141
 Lippi, R. 4, 242, 246
 Lipschutz, A. 1, 191, 160, 2, 34, 53
 Little, C. G. 1, 156, 160
 Liu, C. H. 1, 110, 122
 Ljunggren, H. 4, 109, 113
 Llaurodo, J. G. 4, 293, 297
 Lloyd, C. W. 4, 191, 195
 Lobitz, W. C. 2, 191, 192, 194, 199
 Locke, W. 4, 64, 73
 Lochhead, J. 2, 23, 27, 122, 125
 Loeb, J. 3, 24, 29
 Loeb, L. 1, 146, 157, 158, 160, 2, 41, 51, 54, 55, 69, 70, 71, 71, 80, 81, 84, 161, 172
 Loewhake, H. 2, 196, 197, 199
 Loewer, H. 2, 129, 143
 Logan, M. A. 1, 91, 101
 Logothetopoulos, J. 4, 263, 298
 Lombardo, A. J. 1, 164, 200
 Lombardo, T. A. 4, 281, 281
 Long, C. N. H. 4, 82, 91
 Longley, L. P. 4, 271, 283, 287
 Lorenz, L. 5, 82

- Muntwyler, E. 4, 109, 113
 Mune, A. 3, 15, 18, 5, 54, 92, 102
 Mune, O J. 2, 184, 187
 Murphy, D. P. 5, 262, 264
 Murray, J. E. 4, 45, 57
 Murrell, K. F. H. 3, 166, 169
 Myers, G. B. 4, 289, 296
 Myers, H. L. 2, 41, 54
 Nabarro, I. D. N. 4, 308
 Nadal, J. W. 4, 39, 57
 Nadell, J. 4, 265, 268
 Naeslund, J. 2, 143, 159
 Nagorny, O. V. 3, 51
 Nagy, Z. 4, 284, 286, 296
 Nalbandov, A. V. 2, 81, 83
 Nail, G. H. 5, 153, 165, 176
 Natelson, S. 4, 40, 41, 57
 Ncher, R. 4, 60, 292, 293, 295
 Neil, N. W. 2, 148, 149, 158
 Nelson, J. B. 1, 179, 183
 Nelson, K. R. 4, 82, 93
 Nelson, N. 2, 130, 133, 143
 Nelson, W. P. 4, 45, 57
 Nesbitt, F. B. 2, 141, 143
 Neuburger, A. 1, 100, 103, 217
 Neukirch, F. 232
 Neumann, R. E. 4, 45, 56
 Newman, R. E. 1, 91, 103
 Newman, E. A. 1, 191, 193
 Newman, E. V. 4, 277, 296, 297
 Neyzi, O. 4, 146, 147, 149
 Nichols, M. P. 1, 110, 120, 121, 122
 139, 3, 78, 90
 5, 232, 242
 Nickel, H. K. 1, 109, 111, 114, 115,
 120, 122, 123, 123, 124,
 125, 205, 236, 237, 243
 3, 70, 147, 143
 Nieberle, K. 5, 110, 112
 Nielson, P. E. 2, 148, 159
 Nieto, D. 5, 107, 112
 Nieuwkoop, 1, 56
 Nigrelli, R. F. 5, 113, 138, 147, 176
 178, 210, 211, 212, 213,
 216, 217, 226, 226, 227,
 228, 229, 244, 245
 2, 179, 183
 2, 162, 172,
 173, 4, 90, 93
 2, 86, 96
 4, 220
 1, 66, 3, 77, 90, 91
 1, 196, 200, 3, 24, 29
 101
 2, 81, 83
 1, 198, 200
 2, 36, 54
 O'Brien, J. R. F. 4, 36, 43, 43, 57
 O'Connor, 1, 138
 Ogborn, M. E. 3, 5, 15
 Ohlson, M. A. 1, 122, 123
 Olbnch, O. 1, 30, 51, 52, 138,
 201, 203, 223, 236, 237,
 3, 31, 32, 35, 46, 125, 144,
 147, 148, 183, 190, 191,
 192, 4, 111, 112, 113, 180,
 195, 248
 Olesen, K. H. 4, 102, 110, 113, 113,
 114, 299, 313, 315
 4, 283, 298
 Oliver, B. B. 4, 224, 250, 253, 254, 259
 Olver, J. 3, 26, 29
 Olver, J. A. 4, 109, 113, 114
 Olney, J. M. 2, 81, 83
 Olsen, A. G. 2, 204, 209
 Olsen, C. 5, 99, 103
 Olsson, V. 1, 198, 200
 O Neil, G. C. 5, 235, 236, 241
 Opfinger, E. 1, 89
 Ophuls, W. 4, 23, 24, 32
 Opie, E. L. 3, 75, 90
 Oppenheimer, E. T. 4, 301, 308
 Orent, E. R. 4, 224
 Orent Keleka, E. 3, 10, 18
 Orr, R. T. 1, 145, 160
 Ortiz, E. 5, 190, 191, 193, 198,
 200, 201, 208
 Osterlund, K. 4, 203, 205
 Outler, J. C. 2, 148, 159
 Owen, E. C. 1, 110, 123
 Owens, W. A. 3, 163, 169, 172, 174, 182
 Pacaud, S. 3, 160, 169
 Paccagnella, B. 5, 153, 176
 Pace, N. 4, 289, 298
 Padykula, H. A. 2, 108, 107,
 108, 109, 111, 114
 Page, E. 2, 112, 114
 Page, E. W. 2, 129, 143
 Pain, J. 5, 235, 237, 238, 242, 243
 2, 93, 96
 Palade, G. E. 5, 110, 112
 Pallaske, G. 5, 237, 242, 243
 Palmer, L. S. 2, 3, 3, 11, 13
 Pannabecker, R. F. 2, 41, 54
 Papanicolaou, G. N. 4, 51, 57
 Papper, S. 3, 136, 142
 Parets, A. D. 1, 10, 14
 Park, O. 2, 112, 113
 Parker, F. 4, 102, 102, 106, 108,
 110, 113
 Parker, H. V. 4, 130, 135
 Parker, J. B. 2, 112, 113
 Parker, R. L. 5, 182, 208
 Parker, R. R. 1, 139, 143, 154, 160,
 162, 163, 164, 165, 167,
 168, 169, 170, 171, 172,
 203, 215, 216, 217, 245,
 2, 16, 34, 49, 50, 53, 54,
 55, 56, 57, 58, 60, 65, 66,
 66, 127, 215, 216, 232, 239,
 240, 241, 242, 243, 244,
 245, 246, 248, 249, 3, 30,
 99, 116, 124, 126, 127, 130,
 185, 4, 136

- Marshall, F H A 2, 33, 54, 148
139
- Marshall, R 1, 61, 65
- Marston M 3, 171, 182
- Martin, H E 4, 301, 308
- Martin, W 5, 59 64, 69
- Martinek, J 4, 165, 179
- Massart 4, 75
- Massie, E 4, 280 294
- Master, A M 3, 75, 85, 90
- Masters, W H 2, 113
- Matsumoto K 5, 43, 54
- Matthews, H L 4, 289, 292, 295
- Matthews, L H 2, 37, 54, 56
81, 83, 85, 186, 187
- Mauermayer, G 5, 232 234, 242
- Maurizio, Anna 5, 231 232, 234, 235
236 238 242 243 244
245, 246 248, 254 264
- May, R M 1, 151, 160
- Mayer 2, 173
- Maynard L A 1, 188, 193
3, 8, 18 25 29 5, 183
208, 251 264
- Maynard Smith J 1, 239 240 241
- Maxwell L L 2, 3 10 11 13
- Maxwell M H 4, 274 297
- Meara, P 4, 145 149
- Medawar, P B 1, 4 5 12 15
24 54 78 105 139 169
170 171, 201, 245 2, 199
229 231 3, 5 6 18 5, 271
291
- Meduna 1, 237
- Meggendorfer F 3, 137 143
- Megyesi, K 4, 286, 296
- Mehl, J 4, 301 308
- Meier, R 4, 181 187 194 195
- Mellen, I 5, 217 226
- Mendel, G 4, 208
- Menon M D 4, 149 176
- Menzel, D W 5, 181 184 185 208 210
- Mercier Parot, L 2, 161 163
168 170 172
- Merendino, K A 4, 46 56
- Merkel, J 4, 62 73
- Merrill, A J 4, 271 277 279 297
- Merrill, J P 4, 45 56 57
- Metcalf, L V 1, 221 232 246
- Metchnikoff F 1, 175 181 185
- Meves, I 2, 56 56
- Meyer H 4, 130 133
- Michael, G 2, 202 209
- Michie, D 3, 7 18
- Mickelsen, O 4, 157, 161 162
- Middleworth L van 3, 31 39
- Miescher K 1, 46, 57 138 202
3, 164
- Miley, J I 4, 24 31
- Milinsky, G I 4, 301 303
- Millard A 2, 208 209
- Miller, F J W 3, 95 100
- Miller, G L 4, 238 297
- Miller, J F 4, 301 303
- Miller, J H 1, 220 236, 4, 12,
237, 233, 238, 240, 241, 246
- Miller, L L 4, 133, 135
- Miller, R B 3, 26 29 5, 163, 176
- Milne, M D 4, 93 96, 138, 197,
206, 221, 222, 224, 225,
227, 248, 262 268, 290
297, 299, 300
2, 225, 232
- Miner, C S 4, 267
- Miner, J R 4, 11 34
- Miner, R W 1, 6 4, 250, 259
- Minot, C S 4, 120, 121, 131, 133
- Mitchell, H H 2, 223, 232
- Mitchison, M J 4, 289, 297
- Mollitt G R 4, 254 259
- Morse, T S 4, 227 280 295
297
- Mokotoiff R 1, 164 169 2, 215,
216 221 226 231 232
233 244 235 236, 237
218 219 239 240, 241
242 243 244 245
- Molteni F 3, 9 18 5, 103
- Monakow von 1, 50
- Montagna W 2, 86 91 96 96, 99
101 160 175 188, 191
192 194 199 199, 200
201 211 240 247, 247
243 249 251
- Moon H D 1, 29
- Moore C R 2, 1 11 18 27 34
34
- Moore F D 4, 102 108 110 113
114 291 297
- Moore H I 5, 153 176
- Moore R A 4, 218 246 251 259
- Moore W W 2, 81 83
- Morant G M 1 193 196 200 201
- Morsschi 1, 177 183
- Morgulis S 4, 196 208
- Morris, C J O R 1, 140 137
- Morris, J S 4, 21 31
- Morrison A 4, 226 237 249
- Morrison J I 4, 279 297
- Morrison S 2, 159
- Moskova I 1 179 121 122
- Moskoshjeva A 5, 218 242
- Moskowitz M 2, 225 232
- Mosman H W 2 135 134
- Mother K 2, 506 209
- Moulton C R 4 111 111
- Mounib M S 4, 305 203
- Muehrcke R C 4, 267 297
- Mud Neck O 3 99 106 115 117
118 119 120 124 125
126 127 128 129
110 5, 13 71 80 287
- Muschler A 4, 210 218 242
- Muggleton A 3, 42
- Muir H M 2, 215 112
- Muller A I 4, 292 293 295 297
- Munro H S 4, 190 193
- Munson, P I 2, 162 172

CUMULATIVE AUTHOR INDEX

15

| | | | |
|-----------------|----------------------|-------------------|--------------------------|
| Muntwyler E. | 4 109 213 | Olinch, O | 1 30 51 52, 138 |
| Muric, A. | 3 15 18 5 54 92 | | 201 203 223 236 237 |
| | 102 | | 3 31 32, 35, 46, 125 144 |
| Morie O J | 2, 184 187 | | 147 148 183 190 191 |
| Murphy D P | 5 262 264 | | 192 4, 111 112 113 180 |
| Murray S E. | 4, 43 57 | | 195, 248 |
| Murrell, K. F H | 3, 166 169 | Olesen, K. H | 4, 102, 110 113 113 |
| Myers, G B. | 4 289 296 | | 114 299 313 315 |
| Myers, H L. | 2, 41 54 | | 4, 293 293 |
| Neharro I D N | 4, 308 | Oliver B B. | 4, 224 250 253 254 259 |
| Nadal, J W | 4, 39 57 | Oliver J | 3 26, 29 |
| Nadell, J | 4 265 268 | Oliver J A | 4, 109 113 114 |
| Naglund J | 2, 146 159 | Olney J M | 2, 81 83 |
| Nagorn y O V | 3 31 | Olson A G | 2, 204 209 |
| Nagy Z. | 4, 284 286 286 | O sen, C. | 5 99 103 |
| Na bandov A V | 2, 81 83 | Olsson V | 1 198 200 |
| Nalt G H | 5 153 165 176 | O Ne L, G C | 5, 235 236 242 |
| Natchson, S. | 4 40 41 57 | Opfinger, E. | 1 89 |
| Neher R | 4, 60 292 293 295 | Ophula, W | 4, 23 24 32 |
| Neil, N W | 2, 148 149 158 | Opic, E. L. | 3, 75 90 |
| Nelson, J B | 1 179 183 | Oppenheimer E T | 4, 301 308 |
| Nelson, K. R. | 4, 82 93 | Orent, E. R. | 4 224 |
| Nelson, N | 2, 130 133 143 | Orent Keiles, E. | 3, 10 18 |
| Nelson, W P | 4, 43 57 | Orr R. T | 1, 143 160 |
| Nesbitt, F B | 2, 141 143 | Ortiz, E. | 5 190 191 193 198, |
| Neuberger A. | 1 100 103 217 | Ortiz, I H | 200 201 208 |
| | 232 | Osterland K | 4, 203 205 |
| Neukirch, F | 4 41 56 | Ouller J C. | 2, 148 159 |
| Neuman, R E | 1 91 103 | Owen E. C. | 1 110 123 |
| Newman, E. A. | 1 191 193 | Owens, W A. | 3, 163 169 172 174 182 |
| Newman, E. V | 4, 277 296 297 | | |
| Neyzi O | 4, 146 147 149 | Pacaud, S | 3 160 169 |
| Nichols, M P | 1 110 120 121 122, | Paccagnella, B | 5 153 176 |
| | 139 3 78 90 | Pace N | 4, 289 298 |
| N kel H A. | 5 232 242 | Padykula, H A | 2, 106 107 |
| Nicolaysen, R. | 1 109 111 114 115 | | 108 109 111 114 |
| | 120 122 123 123 124 | Page, E | 2, 122 134 |
| | 125 205 236 237 243 | Page, E. W | 2, 129 143 |
| | 3 70 147 193 | Paun, J | 5 235 237 238 242 243 |
| Nieberle, K. | 5, 110 112 | Palade, G E | 2, 93 96 |
| Nelson F E. | 2, 148 159 | Palaske G | 5 110 112 |
| Nieto D | 5 107 112 | Palmer L S | 5 237 242 243 |
| Nieuwkooop | 2, 56 | Pannabecker R F | 2, 3 3 11 13 |
| Nigrelli, R. F | 5 113 138, 147 176 | Papanicolaou, G N | 2, 41 54 |
| | 178 210 211 212, 213 | Papper S | 4 51 57 |
| | 216 217 226 2 6 227 | Pareia, A. D | 3 136 142 |
| | 228 229 244 245 | Park G | 1 10 14 |
| Nische, H. | 2, 179 183 | Parker F | 2, 112 113 |
| Nixon, W C W | 2, 162 172 | Parker H V | 4 102, 102 106 108, |
| | 173 4 90 93 | | 110 113 |
| No atco J | 2, 86 96 | Parker S B | 4 130 135 |
| No dmann, R. | 4 220 | Parker R. L. | 2, 112 113 |
| Norr, A H | 1, 66 3, 77 90 91 | Parker R. R. | 5 182 208 |
| North oy J H | 1 196 200 3 24 29 | Parkes, A. S | 1 139 143 154 160 |
| | 101 | | 162, 163 164 165 167 |
| Norton H W | 2, 81 83 | | 168 169 170 171 172, |
| Norion, R | 1 158 160 | | 203 215 216 217 245 |
| Nunes, J P | 2, 36 54 | | 2, 36, 34 49 50 53 54 |
| | | | 55 56 57 58 60 65 66 |
| O B en, J R. P | 4 36 41 43 57 | | 66 127 215 216 232 239 |
| O'Connor | 1 138 | | 240 241 242, 243 244 |
| Ogborn, M E. | 5 5 15 | | 245 246 248 249 3, 30, |
| Olson M A | 1 1 2 123 | | 99 116 124 126, 127 130, |
| | | | 185 4 136 |

- Parmington S. L. 4, 228
 Parrish D. B. 4, 200, 205
 Parrott, D. M. V. 4, 257, 259
 Patterson, H. D. 2, 35, 54
 Pearce, J. W. 4, 33, 57
 Percy M. 4, 75
 Pearl R. 1, 243 3, 24, 29 137 143
 5, 267 283
 Pearl, R. de Witt 3, 137 143
 Pearson, E. G. 5, 288
 Pearson J. A. 2, 206, 208 209
 Pearson, K. 1, 32, 238, 3, 8, 18 5, 3
 15 21 31, 53, 54 288
 Pearson O. P. 3, 27 28 29
 Pearson, P. B. 5, 237 242
 Pedersen, S. 4, 39 57
 Pemberton J. 3, 94 100
 Penkew 1, 145
 Penn J. 3, 70 96 100 106 114
 Pepler W. J. 3, 102
 Perks, W. 5, 3 4 5 14 15 81 288
 289 290 291 292, 293
 294 302 303 311
 Perley A. 4, 143 149
 Perrone, J. C. 1, 100 103 2, 217
 232
 Perry S. M. 4, 200 203
 Persike, E. C. 4, 237 259
 Peters, J. P. 4, 38 40 57
 Petrovitch A. 2, 36 37 38 39 41
 42 46 47 53 62 66
 Petter J. E. 3, 28 29
 Petter Roumeaux, A. 3, 17 18 28
 29
 Pettinari, V. 2, 11 54
 Pfeiffer C. A. 1, 151 152 160
 Phillips, E. F. 5, 232 234 242
 Phillips, L. W. 5, 4 5 15
 Phillips, J. B. 5, 149 176
 Phillips, J. C. 1, 111 160
 Phillipson, A. T. 4, 202 205
 Piaget 1, 47
 Pickens, M. 4, 111 115
 Pictet A. 1, 166 200
 Piel H. 5, 59 61 64 69
 Pienaar U. de V. 3, 34 36
 Pierce, E. C. 1, 76
 Piggot, A. P. 1, 18 23 3, 93 100
 Pignard P. 4, 217 219
 Pilcher C. 4, 257 258 266
 Pincus, G. 1, 36 48 126, 126 128
 130 134 136 137 219
 219, 223 224 225 226
 227, 229 230, 232 233
 234 236, 2, 36, 37 54 4,
 90, 93 187 193 262 5,
 267
 1, 201
 von Perquet
 Pirre, G. D. 1, 163 199
 Pitt, F. 3, 10 18
 Pitt, R. F. 4, 263 268
 Platt, R. 4, 50, 56
 Platta, M. M. 4, 263 268
 Plenil, A. A. 4, 89 93
 Pohl, H. A. 2, 109, 113 143, 148
 Polge, C. 1, 163, 164, 169, 2, 215,
 232
 Pollock, W. F. 2, 58
 Polyakov, E. V. 5, 53, 54
 Ponder, L. 2, 217, 223 232
 Ponomareva, L. I. 5, 53, 54
 Pooler N. R. 3, 107
 Popják, G. 2, 217, 232
 Pospelov S. P. 5, 53, 54
 Potter V. R. 4, 133 135
 Power M. H. 4, 41, 56
 Prader A. 4, 60
 Prankerd T. A. J. 2, 233 239 4, 208
 Price, D. 1, 143 160 2, 3 3, 4 13
 14, 15, 17 28
 Primrose T. 4, 89, 93
 Pritchard J. A. 2, 235, 239
 Pritchard J. J. 2, 123, 125
 Pritchard W. H. 4, 271 288 297
 Probst R. T. 5, 144 153 176
 Pucher G. W. 2, 203 209 210
 Puettner 1, 56, 57
 Pycha R. L. 5, 153 176
 Pyrkosch W. 3, 134, 142
 Qasim, S. Z. 5, 153 156, 176
 Quinton A. 4, 109 112
 Quiring, D. P. 8, 119, 133
 Radhakrishnan N. 5, 153 176
 Ragan M. S. 1, 197 200
 Rahm M. P. G. 3, 23, 29
 Rahn O. 1, 173 183
 Raiha N. 4, 204 205
 Raitt D. S. 3, 32 40 5, 149 176
 168 199 200 201 202
 205 208
 Rakowicz M. 5, 153 176
 Ramasarma G. B. 1, 91 94 101
 3, 97 100
 Rand R. W. 2, 81 83
 Ranson R. M. 3, 10 18
 5, 296
 Rao C. R. N. 2, 19 40 42 54
 Rapoport S. 2, 217 230 4, 40
 46 57 287 296
 Rascoff H. 1, 198 200
 Rasmussen A. T. 2, 93 96
 Rasquin, P. 5, 166 208 218 226
 Raven, J. C. 3, 160 168
 Ray L. A. 1, 177 183
 Raynaud A. 2, 1 11 11 167 172
 Reardon, J. B. 4, 45 58
 Rector F. C. 4, 209 210
 Reed R. 3, 63 66 67 68 97 100,
 102 103
 2, 36
 Regan
 Rehm, W. S. 4, 34 31
 Reibach, J. 5, 207 208
 Reid, A. P. 4, 109 111
 Redemeter, E. C. 1, 109 112
 Rejzka, P. 2, 97 68
 Reiman, A. S. 4, 232

| | | | |
|--------------------|-----------------------|-------------------|----------------------|
| Remington J W | 4 275 277 295 | Rolason H D | 4 252 259 |
| Renold A. E. | 4 80 298 | Rolfen G | 4 149 176 |
| Reston, R. M. | 5, 189 207 | Rollins, R. Z. | 5 258 264 |
| Renzi, A. A. | 4 266 | Romanoff A. J. | 3 20 21 30 |
| Re J | 4 286 296 | Romanoff A. L. | 3, 30 21 30 |
| Reynolds, S. R. M. | 2, 80 85 1 9 | Romanoff L. P. | 1 126 136, 137 219 |
| | 143 148 159 | | 219 223 224 225 226 |
| Ribbands, C. R. | 5 232 233 242 | | 227 230 232 233 234 |
| Ribot | 1 33 | | 236 4 90 93 187 195 |
| Rice, T. R. | 5, 170 175 | Romange E. | 4, 130 135 |
| Rich C. O. | 5 4 15 | Rook J. A. F. | 4 301 307 30 3098 |
| Richards, D. W. | 3 79 91 | Rorig, A. | 2 179 183 184 185 |
| Richards, F. J. | 2, 707 709 | | 187 |
| Richardson | 2, 200 | Rorschach H. | 3 181 182 |
| Richardson, I. M. | 3 156 169 | Rosenbaum J. D. | 4 45 51 56 57 |
| Richdale, L. E. | 5 100 101 103 | Rosenberg E. K. | 1 139 3 78 90 |
| Rachel, G. | 4 99 228 62 | Rosenberger C. R. | 5 235 264 |
| Rachie R. | 4, 139 141 149 | Rosenman R. H. | 3, 137 142 |
| Richmond J. | 4 34 | Rosenhal, T. B. | 1 91 99 103 3 97 100 |
| Richter C. P. | 4 166 179 | Ross, G. | 4 277 297 |
| Richter W. | 2 197 199 | Ross M. A. | 4, 256 259 |
| Ricker W. E. | 3 11 19 5 145 | Ro blat J. | 5 15 19 20 86 87 |
| | 149 151 155 176 | | 103 135 177 09 210 |
| Rickham, P. | 4, 98 | | 83 189 290 291 292 |
| Rieser W. H. | 1 197 200 | Roh, C. B. | 2, 165 172 |
| Riesman D. | 1 4 48 49 | Rohman | 2, 201 |
| Ress, B. F. | 3 171 182 | Rohschid P. | 2, 151 158 |
| Rigby B. | 4, 89 90 93 | Roulet, F. | 4 251 259 |
| Risse Th. G. van | 3 170 121 125 | Roule F. C. | 1 16 23 3 93 100 |
| Rinsler M. G. | 4, 89 90 93 | Rounsefel G. A. | 5 197 208 |
| Riondel, A. M. | 4 293 297 | Rous P. | 2, 234 236, 239 |
| Rike, G. | 5 59 69 | Roux, M. | 3 70 96 100 |
| Riesbe g D. | 2, 204 209 | Rowlands, I. W. | 1 142 159 2, |
| Roberts, E. | 1 91 94 103 3 97 100 | | 29 66 69 81 83 83 84 |
| Roberts, J. M. | 2 81 83 | | 85 214 260 |
| Roberts, J. R. E. | 4 75 | Rowntee L. | 4 95 |
| Roberts, P. H. | 1 122 123 | Rowson L. E. A. | 1 164 169 |
| Roberts, R. B. | 2, 148 158 | Rubin B. L. | 1 54 126 130 134 |
| Robertson J. A. | 5 149 176 | | 137 138 139 140 237 |
| Robertson J. J. | 1 155 166 | | 4, 90 93 |
| Robertson O. H. | 2 234 239 | Rubini M. E. | 4, 46, 57 |
| Robertson R. V. | 2, 206 208 209 | Rubner M. | 3 23 30, 5 124 |
| Robertson, T. B. | 1 177 183 5 137 | | 125 126, 127 129 130 |
| Robinson C. V. | 2 130 143 | | 133 134 |
| Robinson, J. R. | 4 23 24 32 214 219 | Rudzinska M. A. | 1 187 193 |
| Robinson, O. J. | 5, 59 69 | | 197 200 3 4 19 |
| Robinson, S. | 4 76 | Ruger H. A. | 3 171 182 |
| Robson J. M. | 2 168 172 | Rumbauer | 5 59 63 69 |
| Rocks em M. | 5 15 31 55 83 84 | Runnstrom S. | 5 149 176 |
| | 112 114 179 210 226 | Ruppe B. | 1 160 |
| | 228 232 234 243 244 | Russel E. S. | 5 190 199 208 |
| | 245 246 247 247 248 | Russe W. I. | 1 155 156 161 |
| | 249 250 251 254 255 | Ru se W. L. | 3 116 125 |
| | 256, 257 258 264 65 | Ryberg, C. | 4 209 219 |
| | 267 68 284 287 89 291 | Ryncarson E. H. | 4 41 56 |
| Rodge, C. E. | 4, 289 298 | | |
| Rodolfo A. | 2, 109 114 118 125 | Sab ne J. C. | 2, 235 239 |
| Rosch G. A. | 5 245 | Sacher G. A. | 5 18 18 31 52 54 |
| Rees le R. | 4, 251 259 | | 80 87 88 104 115 115 |
| Rogerman W. | 5 59 62 69 | | 127 133 133 134 135 |
| Rogers J. B. | 3 11 19 20 30 | | 135 136 137 138 138 |
| Roguski | 4 33 | | 139 140 141 147 176 |
| Rokaw S. N. | 4, 280 294 | | 245 266 282, 284 289 |
| Rolf D. | 4 256 257 259 | | 292, 295 296, 98 |

| | | | |
|---------------------|--------------------------|--------------------|------------------------|
| Parmington S. I. | 4, 223 | Pohl H. A. | 2, 109 113 148, 158 |
| Parnish D. B. | 4, 200 205 | Polge C. | 1, 163 164 169, 2, 215 |
| Parrott, D. M. V. | 4, 257 259 | | 232 |
| Patterson H. D. | 2, 35, 54 | Pollock W. F. | 2, 58 |
| Pearce J. W. | 4, 58, 57 | Polyakov E. V. | 5, 53 54 |
| Pearcy M. | 4, 75 | Ponder, E. | 2, 217, 223 232 |
| Pearl R. | 1, 243 1, 24, 29 157 165 | Ponomareva L. I. | 5, 51 54 |
| | 5, 67 233 | Pooler N. R. | 3, 107 |
| Pearl R. de Witt | 3, 137 143 | Popyák G. | 2, 217 232 |
| Pearson, E. G. | 5, 285 | Pospelov S. P. | 5, 53 54 |
| Pearson J. A. | 2, 206 208 209 | Potter V. R. | 4, 133 135 |
| Pearson K. | 1, 52 233, 3, 8 13 5 3 | Power M. H. | 4, 41, 56 |
| | 15 21 31 53 54 58 | Prader A. | 4, 60 |
| Pearson O. P. | 3, 27 58 29 | Prankerd T. A. J. | 2, 238 259 4, 208 |
| Pearson P. B. | 5, 237 42 | Price D. | 1, 143 160 2, 3 3 4 13 |
| Pedersen S. | 4, 39 57 | | 14 15 17 28 |
| Pemberton J. | 3, 94 100 | Primrose T. | 4, 89 93 |
| Penkow | 1, 145 | Pritchard J. A. | 2, 235 239 |
| Penn J. | 3, 70 96 100 106 114 | Pritchard J. J. | 2, 123 125 |
| Pepler W. J. | 3, 102 | Pritchard W. H. | 4, 271 288 297 |
| Perks, W. | 5, 3 4 5 14 15 81 288 | Probst R. T. | 5, 144 153 176 |
| | 289 290 291 292, 293 | Pucher G. W. | 2, 203 209 210 |
| | 294 302 303 311 | Puettner | 1, 56 57 |
| Perley A. | 4, 143 149 | Pucha R. L. | 5, 153 176 |
| Perrone, J. C. | 1, 100 103 2, 217 | Pyrkosch W. | 3, 134, 142 |
| | 232 | | |
| Perry S. M. | 4, 200 205 | Qasim S. Z. | 5, 153 156, 176 |
| Persike E. C. | 4, 257 259 | Quinton A. | 4, 109 112 |
| Peters, J. P. | 4, 18 40 47 | Quinn, D. P. | 5, 119, 131 |
| Petrovitch, A. | 2, 36 37 5 39 47 | | |
| | 42 46 47 53 62 66 | Radhakrishnan N. | 5, 133 176 |
| Petter J. J. | 3, 25 29 | Ragan, M. S. | 1, 197 200 |
| Petter-Rousseaux A. | 3, 17 18 29 | Rahm M. P. G. | 3, 25 29 |
| | 29 | Rahn O. | 1, 175 183 |
| Pettinari V. | 2, 31 54 | Raiha V. | 4, 204 205 |
| Pfeiffer C. V. | 1, 151 152 160 | Raitt D. S. | 2, 22 30 5, 149, 176 |
| Phillips, E. F. | 5, 232 234 242 | | 168 199 200 201 202 |
| Phillips, E. W. | 5, 4 5 15 | | 205 208 |
| Phillips, J. B. | 5, 149 176 | Rakowicz M. | 5, 133 176 |
| Phillips, J. C. | 1, 155 160 | Ramasarma G. B. | 1, 91 94 103 |
| Phillips, A. T. | 4, 207 205 | | 3, 97 100 |
| Piaget | 1, 47 | Rand R. W. | 2, 31 33 |
| Pickens, M. | 4, 111 115 | Ranson R. M. | 3, 10 13 |
| Pictet A. | 1, 156, 200 | | 5, 296 |
| Piel H. | 5, 59 61 64 69 | Rao C. R. N. | 2, 39 40 42 54 |
| Pienaar U. de V. | 3, 14 6 | Rapaport S. | 2, 237 219 4, 40 |
| Pierce, E. C. | 1, 76 | | 46 47 57 296 |
| Piggot, A. P. | 1, 18 23 3, 91 100 | Rascoff H. | 1, 168 200 |
| Pignard P. | 4, 217 219 | Rasmussen A. T. | 2, 95 96 |
| Pilcher C. | 4, 287 293 296 | Rasquin P. | 5, 196 208 218 276 |
| Pircus, G. | 1, 36 48 126, 126 1, 5 | Raven, J. C. | 1, 160 163 |
| | 150 144 156, 137 219 | Ray L. A. | 1, 177 183 |
| | 219 223 224 225 226 | Raynaud A. | 2, 3 11 13 167 172 |
| | 227 229 230 232 233 | Reardon J. B. | 4, 43 56 |
| | 234 236 2, 36 37 34 4 | Reator F. C. | 4, 209 219 |
| | 90 93 137 195 262 4 | Reed R. | 3, 65 66 67 96 97 100 |
| | 267 | | 102 103 |
| | 1, 201 | Reyan | 2, 56 |
| von Pirquet | 1, 158 199 | Rehm, W. S. | 4, 24 31 |
| Pirre G. D. | 5, 10 18 | Reibsch, J. | 5, 202 208 |
| Pitt J. | 4, 265 268 | Reid, A. F. | 4, 109 113 |
| Pitta, R. F. | 4, 40 56 | Reisenstein, E. C. | 1, 109 122 |
| Platt R. | 4, 265 268 | Reinke P. | 2, 92 96 |
| Plata, M. M. | 4, 69 93 | Reisman A. S. | 4, 222 |
| Plentl, A. A. | | | |

| | | | |
|--------------------|---------------------------|-----------------------|---------------------|
| Sirota, J. H. | 4 288 295 | Sperry, W. M. | 4, 23 32 |
| Sjogren, H. | 3 134 143 | Spiegelman, M. | 3 137 142 |
| Sjogren, T. | 3 134 143 | Spelmeyer, W. | 1 33 48 |
| Sjellavale, L. | 1 109 | Spies, T. D. | 1 198 201 |
| Slack, H. G. B. | 1 100 103 | Spiskaya, T. D. | 5, 53 54 |
| Slater, P. | 1 37 48 | Spolde, H. | 5 64 69 |
| Slater, H. A. | 1 164 169 | Sprague, P. H. | 3 74 75, 76 91 |
| Slavter, J. A. | 2, 215 232 | Spray, C. M. | 4, 120 121 128 |
| Sluiter, J. W. | 5 97 103 | | 136 306 308 |
| Smith | 5, 59 69 | Sproul, E. E. | 4 253 259 |
| Smith, A. D. | 2, 215 216 232 | Spurway, H. | 5 276 281 |
| Smith, A. H. | 4 120, 121 178 181 | Squires, R. D. | 4, 289 297 |
| | 135 254 259 | Stanbury, S. W. | 4 50 56, 193 195 |
| Smith, A. U. | 1 163 164 165 167 | | 267 268 |
| | 168 169 2 215 232 | Stanley, M. W. | 4 128 130 135 216 |
| Smith, A. V. | 2, 33 53 | Stark, W. | 1 194 201 |
| Smith, G. S. | 1 18 | Stark, G. W. | 4 64 65 73 |
| Smith, G. S. an S. | 1 145 161 | Stead, E. A. | 4, 51 57, 271 277 |
| Smith, G. V. | 2, 112 114 | | 298 |
| Smith, H. | 4 227 | Stearns, G. | 4 130 135 |
| Smith, H. L. | 3, 74, 75 76 91 | Steenburg, R. W. | 4 114 |
| Smith, H. W. | 4 230 246 277 298 | Steggerda, F. R. | 4, 120, 121 |
| Smith, J. H. | 1 198 201 | | 131 135 |
| Smith, J. Maynard | 5 16 32, 33 | Steinbach, H. B. | 4 22 32 |
| | 55 86, 87 104 134 137 | Stephenson, R. P. | 4 167 179 |
| | 141 66 267 268 271 | Stens, A. R. | 2, 228 232, 237 238 |
| | 278 279 281 281 282 | Stens, C. F. | 5 21 31 |
| Smith, K. R. | 283 284 285 290 | Stevenson, J. A. F. | 1, 223 232 236 |
| Smith, L. E. | 3 151 169 | Steward, F. C. | 2, 207 209 |
| Smith, L. L. | 1 230 236 | Stewart, J. M. | 2, 236 239 |
| Smith, M. | 5 235 274 | Stewart, W. B. | 2, 236 239 |
| Smith, O. C. | 3 9 19 | Sugall, C. | 4 130 135 |
| Smith, P. E. | 2 112 114 | Stockard, C. R. | 2, 41 54 |
| Smith, P. K. | 1 145 160 | Stockhausner, F. | 5 59 69 |
| Smith, W. J. P. | 4, 120 121 128 131 135 | Stoerk, H. C. | 4, 292 293 296 |
| Snellen, R. C. | 5 145 153 169 175 176 | Stoessiger, B. | 3 171 182 |
| Snyder, D. P. | 2 91 96 | Stolbova, A. | 5 53 54 |
| Snyder, F. F. | 8, 95 103 | Stoll, G. | 4 109 113 |
| Sobel, E. H. | 2, 109 112 113 114 | Stowers, J. M. | 4 308 |
| Soberman, J. | 4, 141 149 | Strangeways, W. M. B. | 4 211 219 |
| Sobers, P. | 4 295 | Strauss, F. | 2, 56 66 67 68 160 |
| Solomon, A. K. | 3, 137 143 | | 174 185 200 |
| Solomon, D. H. | 4 109 112 | Strauss, M. B. | 4 45 51 56 57 |
| | 232 236 3 78 79 90 91 | Strawn, K. | 5 155 176 |
| Solt, F. | 4 235 237 246 | Strong, L. C. | 1 147 161 |
| Sommerson, W. H. | 4, 286 296 | Strube, H. | 3 134 142 |
| Somerville, I. F. | 2, 130 143 | Swart, H. H. C. H. | 4 269 |
| Sonneborn, T. M. | 2, 112 114 | Swau, P. | 5 149 177 |
| | 2, 232 3 16 | Subbarow, Y. | 4 120 135 |
| | 5, 32 35 53 | Sumner, F. B. | 3 9 19 |
| Sontag, L. W. | 34 262 64 | Sumner, J. B. | 1 177 |
| Soudak, S. | 2, 162 172 | Summers-Smith, D. | 5, 99 101 103 |
| Southern, H. N. | 5 255 243 | Sundnes, G. | 4 169 176 |
| Spaček, B. | 5 101 103 | Sutow, W. W. | 4 105 113 |
| Spahr, A. | 4, 291 296 | Sutter, J. | 5 21 31 |
| Spector, H. | 4 60 | Svårdson, G. | 5 171 176 182 190 |
| Spence, J. | 4 131 135 | | 208 |
| Spencer, A. G. | 3 93 100 | Soboda, J. | 5 235 243 |
| Spencer, M. P. | 4 308 | Swanson, M. A. | 2, 136 143 |
| Sperling, G. | 1 183 193 197 200 | Swanson, P. P. | 1 122 123 |
| | 2, 189 199 3, 8 18 5, 251 | Swanson, W. W. | 4 130 135 |
| | 264 | Sward, A. | 1 48 3 159 169 |
| | | Swezy, O. | 2, 35 41 53 54 55 |
| | | Swift, R. W. | 4, 127 135 |

- Sagild, U. 4, 109, 111, 113
 Sakagami, S. F. 5, 233, 243
 Salazar 2, 64, 66
 Samokhvalova, G. V. 5, 209
 Samuels, A. J. 4, 266, 268
 Sander, G. 3, 137, 143
 Sandulesco, G. 1, 130, 137
 Santos, R. F. 4, 46, 57
 Sapsford, C. S. 2, 86, 96
 Sarkar, B. C. R. 5, 237, 243
 Sato, R. 5, 151, 176
 Sawyer, W. H. 4, 167, 179
 Saxl, H. 3, 97, 98, 100, 103;
 5, 113
 Saxon, L. 4, 51, 57
 Saxton, J. A. 4, 253, 257, 259
 Scébat, L. 4, 273, 278, 279, 296
 Schaffer, J. 2, 196, 199
 Schaurmann, O. 4, 167, 179
 Scheerer, M. 3, 180, 182
 Scheidegger, S. 5, 103, 106, 112, 113,
 226
 Scheinberg, P. 3, 147, 4, 286, 297
 Scherer, H. J. 5, 108, 112
 Scheyer, W. J. 5, 89
 Schiefferdecker, P. 2, 188, 199
 Schieren, J. 5, 59, 69
 Schilling, A. 1, 110, 122, 123
 Schloerb 4, 269
 Schloerb, P. R. 4, 109, 113
 Schudlin, J. 4, 181, 195
 Schmidt, C. F. 4, 286, 296
 Schmidt, I. G. 2, 39, 54
 Schmidt, K. P. 1, 10, 14
 Schneider, C. L. 2, 112, 114
 Schneider, F. 5, 240, 243
 Schoenheimer 3, 48, 49
 Schoenheimer, R. 2, 204, 209
 Scholz, W. 5, 107, 112
 Schottler, A. 5, 43, 54
 Schroder, G. 5, 65, 69
 Schroeder, H. A. 4, 288, 297
 Schuler, W. 4, 187, 195
 Schultz, M. O. 1, 192, 193
 Schultze, W. 1, 28, 67, 217
 Schuster, D. 1, 42, 48
 Schutzman, F. L. 4, 301, 308
 Schwartz, I. 4, 274, 297
 Schwartz, I. L. 4, 24, 32, 67, 73, 77
 Schwartz, R. 4, 129, 132, 133,
 135
 Schwartz, W. B. 4, 222
 Schwarz 3, 102, 103
 Schwarz, J. 5, 238, 242
 Schwarz, W. 4, 29, 32
 Scott, J. P. 3, 171, 182
 Scott, W. C. 4, 109, 112
 Scribner, B. H. 4, 46, 56, 93,
 96, 100, 101, 114, 222, 249,
 269
 Scrimshaw, N. S. 1, 198, 200
 Segar, W. E. 4, 113, 134
 Seldin, D. W. 4, 209, 219
 Selkurt, E. W. 4, 274, 277, 297
 Sellers, A. L. 4, 257, 259, 261
 Selwyn, J. G. 4, 199, 203
 Selye, H. 4, 256, 259; 5, 88
 Sen, P. K. 2, 204, 207, 209
 Serane, J. 4, 262
 Serpell, G. 2, 30
 Severinghaus, E. L. 1, 143, 153, 160
 Seville, R. 3, 96, 100
 Seymour, W. M. B. 4, 271, 288, 297
 Shaeffer, K. 4, 130, 135
 Shannon, C. 2, 230, 232
 Sharaf, A. A. 2, 168, 172
 Sheldon, D. S. 4, 109, 113
 Sheldon, J. H. 3, 94, 100, 112, 114;
 4, 264, 268
 Shell, H. M. 5, 237, 243
 Sherman, H. C. 1, 197, 200,
 4, 132, 133, 135
 Shiraishi, Y. 5, 151, 176
 Shirley, R. J. 2, 143, 159
 Shock, N. W. 1, 52, 53, 55, 66, 66,
 110, 120, 121, 122, 139,
 139, 206, 207, 207, 213,
 214, 217, 220, 223, 224,
 229, 230, 231, 232, 236,
 237, 242, 244, 3, 77, 78,
 79, 84, 88, 89, 90, 91, 151,
 168, 4, 11, 12, 111, 112,
 113, 114, 115, 164, 207,
 225, 226, 229, 230, 231,
 232, 233, 235, 236, 237,
 238, 240, 241, 242, 243,
 244, 245, 246, 247, 247,
 248, 249, 250, 264, 268,
 277, 295, 314, 315
 Shohl, A. T. 4, 143, 149
 Shorr, E. 4, 280, 295
 Sieker, H. O. 4, 283, 284, 296, 297
 Silberberg, M. 1, 189, 193
 Silberberg, R. 1, 189, 193
 Silliman, R. P. 5, 149, 176
 Silver, H. M. 3, 75, 80, 90, 91
 Silverstein, I. 1, 180, 183
 Silverstone, F. A. 1, 237;
 3, 77, 80, 90, 91
 Simms, H. S. 5, 72, 73, 74, 75, 76,
 79, 266, 268, 293
 Simon 3, 176
 Simon, E. R. 4, 209, 205
 Simon, E. W. 2, 208, 209
 Simonson, E. 3, 75, 91
 Simpson, A. C. 5, 203, 204, 205, 208
 Simpson, M. E. 1, 29, 2, 33, 54
 Simpson, S. A. 4, 292, 293, 296
 Simpson, T. 4, 267, 268
 Sinclair, H. M. 1, 194, 193,
 197, 200, 201, 202, 203,
 205, 207
 Sinclair, Sir J. 1, 194, 201
 Sinclair-Smith, B. 4, 277, 256
 Singer, B. 4, 181, 195, 297
 Singer, M. 2, 176, 178, 183, 183,
 186, 187
 Singer, R. B. 4, 289, 297

| | | | |
|--------------------|-------------------------|-----------------------|--------------------|
| S. rosa, J. H. | 4 288 95 | Sperry, W. M. | 4 23 32 |
| Sjogren, H. | 3 134 143 | Spiegelman, M. | 3, 137 142 |
| Sjogren, T. | 3 134 143 | Spencer, W. | 1 33 48 |
| Skjellvåg, L. | 1 109 | Spence, T. D. | 1, 198 201 |
| Slack, H. G. B. | 1 100 103 | Spetskaya, T. D. | 5 53 54 |
| Slater, P. | 1 37 48 | Spohde, H. | 5 64 69 |
| Sloviter, H. A. | 1 164 169 | Sprague, P. H. | 3 74 75, 76 91 |
| Solter, J. A. | 2, 215, 232 | Spray, C. M. | 4, 120 121 128 |
| Souter, J. W. | 5 97 103 | | 136 306 308 |
| Smith | 5 59 69 | Sproul, E. E. | 4, 253 259 |
| Smith, A. D. | 2, 215 216 232 | Spurway, H. | 5, 276 281 |
| Smith, A. H. | 4 120 121 128 131 | Squires, R. D. | 4, 289 297 |
| | 135, 254 259 | Stanbury, S. W. | 4 50 56 193 195 |
| Smith, A. U. | 1 163 164 165 167 | | 267 268 |
| | 168 169 2, 215 232 | Staner, M. W. | 4, 128 130 135 216 |
| Smith, A. V. | 2, 33 53 | Stark, W. | 1, 194 201 |
| Smith, G. S. | 1 18 | Stark, G. W. | 4 64 65 73 |
| Smith, G. van S. | 1 145 161 | Stead, E. A. | 4 51 57 271 277 |
| Smith, G. V. | 2, 112 114 | | 298 |
| Smith, H. | 4 227 | Stearns, G. | 4 130 135 |
| Smith, H. L. | 3 74 75 76 91 | Steenburg, R. W. | 4 114 |
| Smith, H. W. | 4 230 246, 277 298 | Steggerda, F. R. | 4 120 121 |
| Smith, J. H. | 1 198 201 | | 131 135 |
| Smith, J. Maynard | 5 16 32, 31 | Steinbach, H. B. | 4, 22 32 |
| | 55 86 87 104, 134 137 | Stephenson, R. P. | 4 167 179 |
| | 141 66, 267 268 271 | Stens, A. R. | 2 228 237 237 238 |
| | 278 279 281 281 282 | Stevens, C. F. | 5 21 31 |
| | 83 284 285 290 | Stevenson, J. A. F. | 1 223 232 236 |
| Smith, K. R. | 3 151 169 | Steward, F. C. | 1, 07 209 |
| Smith, L. E. | 1 230 236 | Stewart, J. M. | 2, 236 239 |
| Smith, L. L. | 5 155 174 | Stewart, W. B. | 2, 236 239 |
| Smith, M. | 3 9 19 | Stigall, C. | 4 130 135 |
| Smith, O. C. | 2, 112 114 | Stokard, C. R. | 2, 41 54 |
| Smith, P. E. | 1 145 160 | Stoklausner, F. | 5, 59 69 |
| Smith, P. K. | 4, 120 121 128 131 135 | Stork, H. C. | 4 292 293 296 |
| Smoly, W. J. P. S. | 145 153 169 175 176 | Stones, G. B. | 3 171 182 |
| Sniffen, R. C. | 2 91 96 | Stolbova, A. | 5 53 54 |
| Snyder, D. P. | 5 95 103 | Stoll, G. | 4 109 113 |
| Snyder, F. F. | 2, 109 112 113 114 | Stowers, J. M. | 4, 308 |
| Sobel, E. H. | 4 141 149 | Strangeways, W. M. B. | 4, 211 219 |
| Soberman, J. | 4, 295 | Strauss, F. | 2 56 66 67 68 160 |
| Sobye, P. | 3, 137 143 | | 174, 185 200 |
| Solomon, A. K. | 4 109 112 | Strauss, M. B. | 4 45 51 56 57 |
| Solomon, D. H. | 1 139 223 2 4 229 | Strawn, K. | 5 155 176 |
| | 232 236 3 78 79 90 91 | Strong, L. C. | 1 147 161 |
| | 4 235 237 246 | Strube, H. | 3 134 142 |
| Sol, F. | 4 286 296 | Stuart, H. A. C. H. | 4 269 |
| Sommerson, W. H. | 2, 130 143 | Suav, P. | 5 149 177 |
| Somerville, F. | 2 112 114 | Subbarow, Y. | 4 120 135 |
| Sonneborn, T. M. | 2, 252 3, 16 | Sumner, F. B. | 3 9 19 |
| | 5 32 35 53 | Sumner, J. B. | 1 177 |
| | 54 262 64 | Summers, Smit, D. | 5 99 101 103 |
| Sontag, L. W. | 2 162 172 | Sundnes, G. | 5, 169 176 |
| Soudak, S. | 5 235 243 | Sutow, W. W. | 4 105 113 |
| Southern, H. N. | 5 101 103 | Sutter, J. | 5 21 31 |
| Spadek, B. | 4 291 296 | Sardson, G. | 5 171 176, 182 190 |
| Spahr, A. | 4, 60 | | 268 |
| Spector, H. | 4, 131 135 | Soboda, J. | 5 235 243 |
| Spence, J. | 3 95 100 | Swanson, M. A. | 2, 136 143 |
| Spencer, A. G. | 4 308 | Swanson, P. P. | 1 122 123 |
| Spencer, M. P. | 4 274 277 297 | Swanson, W. W. | 4 130 135 |
| Sperling, G. | 1 188 193 197 200 | Sward, K. | 1 48 3 159 169 |
| | 2, 189 199 3 8 18 5 251 | Swezy, O. | 2, 35 41 53 54 55 |
| | 264 | Swift, R. W. | 4 127 135 |

- Swyer, G I M 2, 174, 175, 4, 13, 78 93,
 94 95, 97, 98, 115, 197,
 198, 227, 260, 313, 316
 5, 155, 175, 228
 de Sylva, D 3, 103
 Szabó 4, 284, 286, 296
 Szabó, G 1, 211, 213 3, 160,
 162, 169
 Szafran, J 4, 286, 296
 5, 19, 129 133, 289
 Szász, J
 Szilard L. 5, 21, 31
 Tabah, L. 5, 92 94 103
 Taber, R D 4, 38 56
 Taffel, M 5, 136
 Tainter, M L 4, 292 293 296
 Tait, J F 4, 45 57, 284, 286
 Takács, L. 296
 Talbot, F G 3, 9 18
 Talbot, N B 4, 13 32, 64 73 76,
 94 97, 100 105 113 137
 139, 139 140 141 143,
 146 147 149 150 151,
 152, 162 163 226 260
 261, 317
 2, 197 199
 4, 221
 3, 24 30
 2, 179 183
 2, 141 143
 1, 197 201
 Tannenbaum A 4, 80 93 5 84 85
 Tanner J M 86 88 266 290, 296 297
 5, 232 242
 Tanquary M C 3, 96 100
 Tattersall R N 5, 277 281
 Tauber O E. 4 40 57
 Tayler R Q C 4 116
 Taylor A 5, 149 167 177
 Taylor C C 3, 188
 Taylor D J 4, 157 161 162
 Taylor H L. 4, 36 41 43 57
 Taylor W H 2, 162 172
 Teel H M 5, 146 151 177
 Templeman W 2, 207 209
 Templeman W G 1, 197 201
 Templeton H A 3 10 18
 Tener J S 3, 120 125
 Tengbergen W van E 2, 110 112 114
 Tenney B 3, 24 30
 Terao A 1, 40, 48 3, 172 174
 Terman L. M. 182
 5, 182 208
 Terpenning J G 4, 139 140 141 145
 Terry M 146 147 149
 5, 149 177
 Tester A L 4, 62 63 64 65 67
 Thaysen, J H 68, 69 72 73 73 74 74
 75 76 77 77 94 99
 4, 273 278
 279 296
 Théard, A 2, 120 121 125 127
 5, 3 15
 4, 81 93 262
 Thomasson, B 4, 273, 283 298
 Thompson, J C. 4, 79 93 97, 98
 Thompson, J F 2, 207, 209
 Thompson, W F 5, 151, 177
 4, 41, 56
 Thomsen, A. C. 2, 110, 112 114
 5, 33
 Thomsen, K. 4, 82, 93
 Thomson, A M 4, 82 93 280, 298
 Thorn, D W 4, 63, 65, 67 68,
 73 76
 Thorn, G W
 Thorn, N A
 Thorndike, E. L. 3, 162 169,
 172 182
 3, 178, 182
 Thorndike, R L. 3, 119, 121, 123
 Thung, P J 3, 181, 182
 Thurstone, L. L. 5, 149, 177
 Tibbo, S N 5, 155, 177
 Tiews, K 4, 266, 269
 Timoner, J 1, 138
 Tizard 5, 237, 243
 Todd F E. 4, 200, 205
 Topper, Y J 1, 110, 121, 122
 Toro, G 4, 206
 Tosteson, 5, 217, 226
 Townsend C H 5, 262, 264
 Tracey K M 4, 131, 133
 Trowbridge, P F 1, 145
 Tschertok 2, 189 199
 Tsuchiya K. 2, 84,
 Tuchmann Duplessis, H 127 161 163 168 172
 173 174 175 245
 5, 174 177
 3, 166 169
 4, 126 136
 4, 301 307 308 309
 1 1 23 48, 50, 52,
 53 54 57 67 68, 104 105,
 107 108 125 137 138
 205 206, 238 241 245
 3 46, 65 66 67 69 71,
 72 92 96 97 100 102
 103 128 182, 183
 2, 18 27
 2, 236 239
 Turner C D
 Turner J R
 Ueberwasser H 4, 181 193
 3, 32 59
 Ullmann E A 3, 96 100
 Unna P G
 Vaas, A. F 5, 170 177
 4 165 185 187
 Vacek Z 4, 291 296
 Valach A 5, 134
 Vallois H V 5, 179
 Van Cleave H J 4, 109 112
 Vanderhinde R J 2, 36 44 45
 Van Eck G J V 46 54 55
 5 97 103
 Van Heerde P F 4, 248 272 298
 Van Slyke, D D 1 153 161
 Van Wageningen G 4, 201 205
 Vara, P 4, 161 162
 Varga, F 4, 273 283 298
 Varnauskas, E

- Velardo, J. T. 2, 81, 83
 Verney, E. B. 4, 37, 57
 Vernon, E. H. 4, 89, 93, 293, 294
 Vershuer, O. v. 3, 137, 431
 Verze, F. 1, 24, 57, 67, 68, 108, 171,
 204, 238, 3, 30, 60, 63,
 64, 66, 67, 68, 69, 70,
 94, 128, 194, 5, 82, 85, 86,
 112, 133, 137, 138, 141, 298
 Verzar, J. 1, 215, 216
 Verzar-McDougall, J. 3, 64, 68, 187
 Vau, W. N. 4, 283, 298
 Vickery, H. B. 2, 203, 209, 210
 Videbeck, A. 4, 241, 246
 Vilce, C. A. 2, 17, 28, 107, 112, 114,
 117, 129, 136, 141, 142,
 143, 144, 145, 146,
 147, 212, 213, 242, 243,
 245, 249, 250, 253
 Vincent, D. F. 1, 37, 48
 Vischer, A. L. 1, 16, 23, 25, 49, 66,
 3, 93, 100
 Vischer, M. B. 1, 179, 180, 185
 Vitt, V. O. 5, 35, 43, 46, 49, 54
 Vives, F. 5, 149, 177
 Vivino, E. 5, 237, 238, 242, 243
 Vizoso, M. 3, 10, 18
 VNIRO 5, 149, 177
 Vogt, C. 1, 35, 48, 49
 Vogt, F. 2, 184, 187
 Vogt, O. 1, 33, 48, 49, 3, 147
 Vonöckty, J. 4, 161, 162
 Voogd, S. 5, 237, 243
 Vosburgh, G. J. 2, 111, 112, 113,
 148, 159
 Vosa, H. E. V. 2, 34, 53
 Wackwitz, J. D. 3, 165, 169
 Waelch, L. 2, 197, 199
 Wagenen, G. van 2, 33, 54
 Waggoner, R. W. 3, 134, 143
 Wagman, I. H. 3, 77, 91
 Wahl, G. 5, 235, 243
 Wakman, A. J. 2, 203, 210
 Walaa, E. 2, 133, 144
 Walaa, O. 2, 133, 144
 Waldeyer, L. 1, 145, 161
 Waldo, C. M. 2, 177, 178, 179,
 180, 182, 183, 184, 185
 Walford, L. A. 5, 159, 177, 214, 226
 Walker, A. R. P. 3, 110, 114, 189
 Walker, E. P. 5, 119, 133
 Walker, W. G. 2, 148, 159
 Wallace, B. 5, 20
 Wallace, J. G. 3, 163, 168
 Wallace, W. 5, 189, 208
 Wallace, W. M. 4, 34, 58, 59,
 74, 75, 98, 116, 120, 129,
 132, 133, 134, 135, 136,
 137, 138, 152, 164, 224,
 225, 226, 227, 316
 Wallart, J. 1, 145, 161
 Walliker, C. 1, 197, 200
 Walton, W. S. 3, 95, 100
 Wang, H. 2, 34, 54
 Wang, H. W. 2, 129, 144
 de Wardener, H. E. 4, 54, 57, 150
 Ward, B. 2, 30
 Warkany, J. 2, 165, 172
 Warmug-Larsen 4, 73
 Warner, F. G. 4, 289, 298
 Warnock, W. M. 4, 309
 Warren, F. L. 4, 202, 203, 205
 Warren, J. V. 4, 271, 298
 Watchorn, E. 4, 100
 Watkin, D. M. 1, 206, 207, 3, 79, 88, 91;
 4, 226, 231, 233, 244, 246
 Watson, M. 2, 86, 96
 Watts, R. M. 1, 151, 158, 160;
 2, 162, 172
 Waymouth, C. 1, 191, 193
 Weatherford, H. L. 2, 176, 183
 Weaver, N. 5, 237, 243
 Weaver, W. 2, 230, 232
 Webb, C. S. 5, 104
 Weber, R. 5, 43, 54
 Weidenreich, F. 5, 134
 Weil, W. B. 4, 116
 Weir, J. P. 4, 95
 Weissman, R. 2, 235, 238
 Weissmann 3, 4
 Weiss, J. M. 2, 101, 103
 Weitnauer, E. 5, 104
 Weizel, N. C. 1, 198, 201
 Welford, A. T. 1, 41, 48, 209, 210,
 213, 215, 3, 71, 149, 160,
 162, 169, 182, 183, 184,
 186, 187
 Wells, H. G. 1, 89
 Wells, L. J. 2, 3, 10, 11, 12, 13
 Well, L. G. 4, 75
 Wendt, W. E. 4, 283, 296
 Wener, J. 4, 297
 Wenner, R. 1, 151, 161
 Werko, L. 4, 273, 279, 280, 283, 293,
 298
 Wertber, M. 4, 62, 73
 Wertman, M. 4, 301, 308
 Wesman, A. G. 3, 174, 182
 Wesson, L. G. 4, 277, 298
 West, A. S. 5, 258, 264
 West, C. 2, 206, 209
 West, C. D. 4, 40, 46, 57, 120,
 121, 132, 134
 Westman, A. 2, 49, 54, 145, 161
 Weston, H. C. 3, 162, 164, 169
 Weston, R. E. 4, 280, 293
 Wetstein, A. 4, 94, 181, 195
 Wetzel 3, 184
 Weyer, F. 5, 234, 243
 Weygand, F. 5, 237, 243
 Wheeler, N. C. 4, 275, 277, 293
 Whipple, G. H. 4, 192, 193, 195
 White, A. G. 4, 99
 White, H. L. 4, 256, 257, 259
 White, P. 5, 267
 White, V. K. 2, 141, 144
 Whitehouse, A. G. R. 4, 63, 73

- Swyer, G I M 2, 174 175 4, 13 78 93,
94, 95 97, 98 115 197
198, 227, 260, 313, 316
- de Sylva, D 5, 155, 175, 228
- Szabó 3, 103
- Szabó G 4, 284 286, 296
- Szafran, J 1, 211, 213 3, 160
162, 169
- Szász, J 4, 286 296
- Szilard, L 5, 19, 129 133 289
- Tabah L 5, 21, 31
- Taber, R D 5, 92 94 103
- Taffel, M 4, 38 56
- Tainter, M L 5, 136
- Tait, J F 4, 292 293 296
- Takács, L 4, 45 57, 284, 286
296
- Talbot F G 3 9 18
- Talbot N B. 4 13 32 64 73 76
94 97 100 105 113 137,
139, 139, 140, 141, 143
146 147 149 150 151,
152 162 163 226, 260
261 317
- Talke, L 2, 197 199
- Tallqvist H 4, 221
- Tanaka T 3, 24 30
- Tandler J 2, 179 183
- Tang C T 2, 141 143
- Tannenbaum A 1, 197 201
- Tanner J M 4 80 93 5 84 85
86 88 266 290 296 297
- Tanquary M C 5, 232 242
- Tattersall R N 3 96 100
- Tauber O E 5 277 281
- Taylor R Q C 4, 40 57
- Taylor A 4, 116
- Taylor C C 5, 149 167 177
- Taylor D J 3, 183
- Taylor H L 4, 157 161 162
- Taylor W H 4 36 41 43 57
- Teel H M 2, 162 172
- Templeman W 5, 146 151 177
- Templeman W G 2, 207 209
- Templeton H A 1, 197 201
- Tenér J S 3, 10 18
- Tengbergen W van E 3 120 125
- Tenney B 2, 110 112 114
- Terao A 3, 24 30
- Terrian L M 1, 40 48 3 172 174
182
- Terpenning J G 5 182 203
- Terry M 4, 139 140 141 145
146 147 149
- Tester A L 5, 149 177
- Thaysen, J H 4, 62 63 64 65 67
68, 69 72 73 74 74
75 76 77 77 94 99
- Théard A 4, 273 278
279 296
- Thelander H 2, 120 121 123 127
- Thiele T N 5 3 13
- Thomas, W A 4, 81 93 262
- Thomasson B 4, 273 283 298
- Thompson, J C 4, 79 93 97, 98
- Thompson, J F 2, 207, 209
- Thompson W F 5, 151 177
- Thomsen A C 4, 41, 56
- Thomsen K 2, 110, 112 114
- Thomson A M 5, 33
- Thorn, D W 4, 82 93
- Thorn, G W 4, 82 93 280 298
- Thorn, N A 4, 63, 65, 67 68,
73, 76
- Thorndike E. L. 3, 162 169
172 182
- Thorndike, R L 3, 173 182
- Thung P J 3, 119, 121 125
- Thurstone L. L. 3, 181, 182
- Tibbo S N 5, 149 177
- Ticwa, K 5, 155 177
- Timoner, J 4, 266, 268
- Tizard 1, 138
- Todd F E. 5, 237, 243
- Toppet Y J 4, 200 205
- Toro G 1, 110, 121 122
- Tosteson 4, 206
- Townsend C H 5, 217 226
- Tracey, h M 5, 262 264
- Trowbridge, P F 4, 131, 135
- Tschertok 1, 145
- Tsuchiya K 2, 189 199
- Tuchmann Duplessis H 2, 84,
127 161 163 168 172
173, 174 175 245
- Tucker D W 5, 174 177
- Tucker W A 3, 166 169
- Tudvad F 4 126 136
- Tufts, E V 4 301 307 308 309
- Tunbridge R E 1 1 23 48 50, 52,
53 54 57 67 68 104 105
107 108 125 137 138
205 206, 238 241 245
3 46 65 66 67 69 71,
72 92 96 97 100 102
103 128 182, 183
- Turner C D 2 18 27
- Turner J R 2, 236 239
- Ueberwasser H 4, 181 195
- Ullmann L A 3 52 59
- Unna P G 3, 96, 100
- Vaas, h F 5 170 177
- Vacek Z 4 165 185 187
- Valach A 4, 291 296
- Vallois, H V 5, 134
- Van Cleave H J 5 179
- Vanderlinde R J 4 109 112
- Van Eck G J V 2, 36 44 45
46 54 55
- Van Heerde, P I 5, 97 103
- Van Slyke, D D 4, 249 272 298
- Van Wagenen G 1 133 161
- Vara, P 4, 203 205
- Varga, F 4, 161 162
- Varnauskas, E. 4, 273 283 298

SUBJECT INDEX

Figures in heavy type indicate volume number Figures in ordinary type indicate page number

- Acid-base balance, changes in due to age
4, 224-245
development of 4, 209-223
during menstrual cycle, 4, 93
in foetal life, 4, 217-219
in old age, 4, 242-243
- Acipenser* arteriosclerosis in, 5, 109
- Achievements in later life, 1 39-40, 50-51
- Achilles tendon, age changes in structure of 3, 68-69
- Acid phosphatase in placenta, 2, 107-108
- Acipenser fulvescens* survival curves of 5, 143-144
- Acipenser ruthenus* oldest age of 5, 191
- Acipenseriformes*, lifespan of 5, 220-222
lifespan and size of 5 152
- ACTH, administration of in aged schizophratics, 1 230-236, 237
effect on adrenals, 4, 175
effect on glycogen storage, 2, 24-25-29
effect on hair 2, 175
effect on potassium excretion, 4 176-177-178
effect on schizophrenic patients, 1, 229
effect on sodium excretion, 4 176, 177-178
effect on water loss, 3, 176-177-178
response to in old age 1 139
- Actuarial aspects of human lifespan, 5 2-20
- Adaptation, decline of 3, 62, 63
definition of 3 61
in study of ageing 3 60-67-71
- Adenosine triphosphate, in placenta, 2, 107-108
in red cells, 2, 238
- Adjustment in old people, 1 41-42, 43-46-47
- Adolescence, water and electrolyte changes during, 4, 80-81
- Adrenal cortex, activity of in elderly schizophrenic patients, 1 219-238
mitochondria in 2, 101-102, 103
relationship with pituitary gland 2, 22
- Adrenal corticosteroids, excretion of changes due to age, 4 91
- Adrenal glands, control of sodium intake by 4, 166
effects of ACTH and cortisone, 4, 175-176
effect of castration, 4, 197-198
effect on diuresis, 4 113
mitochondria in 2, 101-102
- Adrenal hyperplasia, effect on water and electrolytes, 4, 79-80
- Adrenal steroids, biosynthesis of 1, 126-128-129-133
effect of age on influence of 4, 192-194
effect on kidney 4, 257-262
effect on water and electrolyte excretion, 4 180-194-196-198
excretion of age changes in 1, 126-140
relationship with urinary ketosteroids, 1, 128-130-133-139
- Adrenalectomy effect on rats, 2, 58
- Adrenaline effect on water diuresis, 4, 9-14
in erythraemia, 1, 67
- Adrenosterone, administration of in old age, 1 134-136
- Adults, water in body of 4, 106-110
- Aedes aegypti*, effect of diet on 5, 253
- Africans, ageing in, 3, 34-104-114
carcinoma in 3 104-106-113
liver disease in, 3 188-190
malnutrition in, 3, 104-114-145-188-190
mental disease in 3 145
nutrition in 3 188-190
- Age, body water changes due to 4, 110-112, 114, 115
causing changes in acid base balance 4 224-225
causing changes in effect of aldosterone on urine 4, 182-187
causing changes in effect of pitressin, 4, 239-240
causing changes in extracellular water 4, 31-110-112, 114-115
causing changes in glomerular filtration rate, 4, 231-238-246
causing changes in haemoglobin, 4, 203-206-207
causing changes in hormonal control of homeostasis, 4, 168-179
causing changes in intracellular water 4, 110-112, 114-115
causing changes in nitrogen excretion 4 243
causing changes in oestrogen excretion 4, 91
causing changes in steroid metabolism 4, 90-92
cellular changes due to 4 199-203
changes due to in fish, 5, 218

| | | | |
|--------------------|----------------------|------------------------|-----------------------|
| Whitney L. F. | 1, 155 161 | Wolstenholme, G. E. W. | 5, 71 |
| Widdas W. F. | 2, 118 119 120 | Wood G. C. | 3, 66, 68 98 100 |
| | 125 4 201 203 205 | Wood J. G. | 2, 203 210 |
| Widdowson E. M. | 1 186 195 | Wood M. J. | 3, 97 100 103 |
| | 193 201 4, 13 96 97 | Wood T. R. | 3, 24 29 |
| | 113 114 120 121 128 | Woodford Williams, E. | 4 111 |
| | 136 136 137 160 162 | | 112 113 180 193 |
| | 163 164 180 195 199 | Woodger J. H. | 2, 86 96 |
| | 203 203 208 209 215 | Woollard H. H. | 2, 189 199 |
| | 217 219 221 222 305 | Worcester J. | 4, 64 73 |
| | 306 308 309 | Wright A. W. | 1, 146 161 |
| Wieland P. | 4 181 195 | Wright N. C. | 5, 59 69 |
| Wiesner B. P. | 1, 152 161 | Wright P. L. | 2, 81 83 |
| Willesworth V. B. | 5 87 133 240 | Wrong O. | 4, 46 57 266 268 |
| | 243 243 245 267 285 | Wurzel W. | 5, 59 69 |
| Wilde E. | 1, 198 201 | Wussow W. | 5, 66, 67 69 |
| Wilde, W. S. | 2, 111 112 | Wyburn G. M. | 2 41 53 |
| | 113 148 159 | Wynn V. | 4 145 149 |
| Wilens S. L. | 4 253 259 | Wynne Edwards V. C. | 5 193 |
| Wilkes A. | 5 258 264 | | 194 195 208 |
| Wilkins L. | 4 79 93 | | |
| Wilkinson C. F. | 3, 137 143 | Yannet H. | 4 106 113 |
| Wilkinson E. | 4 6 11 | Yemm E. W. | 2, 145 202 203 204 |
| Williams, I. T. D. | 4 283 295 | | 208 209, 210 210 211 |
| Williams, J. N. | 4 133 136 | | 212 213, 214 241 242 |
| Williams, P. C. | 2 58 59 60 63 66 | | 249 |
| | 66 67 68 145 174 175 | Yerkes A. | 5 119 133 |
| | 213 242 243 247 249 | Yerkes J. | 3 179 182 185 |
| | 252 | Yerkes R. | 5 119 133 |
| Williams, R. G. | 2, 91 95 96 | Yerushalmy J. | 5 21 31 53 54 |
| Wills K. | 4, 283 298 | Yengst M. J. | 1 706 207 3 77 |
| Willius, F. A. | 3 74 75 76 91 | | 88 91 4 242 244 245 |
| Wilson C. | 4 258 259 | | 246 47 |
| Wilson C. P. | 4 287 296 | Yockey H. P. | 5 129 133 |
| Wilson I. | 5 21 31 | Yokota T. | 5 155 163 177 |
| Wilson J. W. | 2 251 | Young F. G. | 2 162 166 167 172 174 |
| Wilson R. C. | 1 40 48 | Young I. M. | 2 221 232 236 238 |
| Witner W. | 4 284 286 296 | Young L. E. | 2 236 238 239 |
| Wiltshire, G. H. | 2 704 209 | Young P. T. | 4 166 179 |
| Wimsatt W. A. | 2 155 158 159 | Young W. C. | 1, 149 161 2 41 54 |
| Winwarther H. de | 2 42 54 | Young W. F. | 4 38 40 41 56 57 59 |
| Winnstedt R. | 5 59 69 | | 59 96 162 |
| Winsatt W. A. | 2 106 114 | Yudin J. | 1 192 193 4 209 219 |
| Winslow J. A. | 4 275 277 295 | | |
| Wise G. H. | 4 700 705 | Zahl P. A. | 5 267 |
| Wislocki G. B. | 2, 27 98 103 104 | Zamyat N. N. | 5 53 54 |
| | 105 106 107 108 109 | Zander E. | 5 212 43 |
| | 110 112 113 114 115 | Zawadowsky M. M. | 2 179 183 |
| | 116 129 144 147 159 | Zeman F. D. | 3 147 |
| | 176 176 177 178 179 | Zegenhagen G. | 5 59 60 64 69 |
| | 180 181 182 183 184 | Zill A. | 3 190 |
| | 184 185 185 186 187 | Zinna N. V. | 3 133 142 |
| | 191 192 198 241 243 | Zlotnik J. | 2 86 96 |
| | 246 248 249 251 4 | Zonneveld R. J. v. | 3 95 100 |
| | 217 219 | Zorzi G. | 2, 191 192 199 |
| Witschi E. | 2, 14 15 17 | Zuckerman S. | 1 144 145 149 160 |
| Witwer S. H. | 5 237 243 | | 161 2, 15 28 31 11 |
| Wohlschlag, D. L. | 5 145 151 177 | | 32 33 34 35 38 49 50 |
| Woke, P. A. | 5 255 264 | | 51 53 54 55 56, 57 58 |
| Wolfe J. M. | 1 146 161 | | 60 65 66 66 67 98 126 |
| Wolff | 2, 56 | | 184 187 201 3, 127 4 |
| Wolff H. P. | 4 280 292 293 298 | | 82 93 251 259 |
| Wolkoff K. | 5 110 112 | Zwebach B. W. | 4, 80 293 |
| Woll E. | 1 145 161 | Zweymüller E. | 4, 220 221 246 |

SUBJECT INDEX

Figures in heavy type indicate volume number Figures in ordinary type indicate page number

- Acid base balance, changes in due to age
4, 224-45
development of 4, 209-223
during menstrual cycle 4, 93
in foetal life, 4, 217-219
in old age, 4, 242-243
- Accipiter* arteriosclerosis in 5 109
- Achievements in later life, 1 39-40 50, 51
- Achilles tendon, age changes in structure of 3, 68-69
- Acid phosphatase in placenta, 2, 107-108
- Acipenser fulvescens* survival curves of 5, 143-144
- Acipenser ruhenus* oldest age of 5 191
- Acipenseriformes*, lifespan of 5, 220-222
lifespan and size of 5 152
- ACTH, administration of in aged schizophrenics, 1 240-236 237
effect on adrenals, 4 175
effect on glycogen storage, 2, 24-25 29
effect on hair 2, 175
effect on potassium excretion, 4 176
177-178
effect on schizophrenic patients, 1 229
effect on sodium excretion, 4 176 177
178
effect on water loss 3 176, 177-178
response to in old age, 1 139
- Actuarial aspects of human lifespan, 5 2-20
- Adaptation, decline of 3, 62, 63
definition of 3 61
in study of ageing, 3 60-67 71
- Adenosine triphosphate in placenta, 2, 107-108
in red cells, 2, 238
- Admixture in old people, 1 41-42, 43-46, 47
- Adolescence, water and electrolyte changes during 4, 80-81
- Adrenal cortex, activity of in elderly schizophrenic patients, 1 219-238
mitochondria in 2, 101-102, 103
relationship with pituitary gland, 2, 22
- Adrenal corticosteroids, excretion of changes due to age, 4, 91
- Adrenal glands, control of sodium intake by 4, 166
effects of ACTH and cortisone, 4, 175-176
effect of castration, 4, 197-198
effect on diabetes, 4 11
mitochondria in, 2, 101-102
- Adrenal hyperplasia, effect on water and electrolytes, 4, 79-80
- Adrenal steroids, biosynthesis of 1, 126-128 129-133
effect of age on influence of 4 192-194
effect on kidney 4, 257-262
effect on water and electrolyte excretion 4, 180-194 196-198
excretion of age changes in 1 126-140
relationship with urinary ketosteroids, 1 128-130, 133-139
- Adrenalectomy effect on rats, 2, 58
- Adrenaline, effect on water diuresis, 4, 9
14
in emphysema, 1 67
- Adrenosterone, administration of in old age, 1 134-136
- Adults, water in body of 4 106-110
- Aedes aegypti* effect of diet on 5 255
- Africans, ageing in, 3 34 104-114
carcinoma in, 3 104-106 113
liver disease in, 3 188-190
malnutrition in, 3 104-114 145 188-190
mental disease in, 3 145
nutrition in, 3 188-190
- Age, body water changes due to 4 110-112, 114-115
causing changes in acid base balance, 4, 224-225
causing changes in effect of aldosterone on urine 4 183-187
causing changes in effect of pressure, 4 239-240
causing changes in extracellular water 4, 31 110-112, 114-115
causing changes in glomerular filtration rate, 4, 231 238-246
causing changes in haemoglobin, 4 203-206 207
causing changes in hormonal control of homeostasis, 4, 168-179
causing changes in intracellular water 4, 110-112 114-115
causing changes in nitrogen excretion 4, 243
causing changes in oestrogen excretion 4, 91
causing changes in steroid metabolism 4, 90-92
cellular changes due to 4 199-205
changes due to in fish, 5, 218

Age

- changes in ketosteroid excretion due to, 4, 91
 - effect of fecundity in fish, 5, 198-200 201
 - effect on blood volume, 4, 243
 - effect on cells, 4, 199-205
 - effect on deer antler growth, 2, 183-184
 - effect on diuresis, 4, 6-10
 - effect on fecundity in fish, 5, 201
 - effect on homeostasis, 4, 139-153
 - effect on influence of adrenal steroids, 4, 192-194
 - effects on insects, 5, 247-268
 - effect on kidney, 4, 11-12, 227-228 229-249, 253-254
 - effect on oestrogen excretion, 4, 91
 - effect on renal disease, 4, 250-263
 - effect on reproduction, 5, 181-182
 - effects on reproduction in fish, 5, 186-206
 - effect on starvation, 4, 226
 - effect on water diuresis, 4, 238-240
 - electrolyte changes due to, 4, 241-311-312
 - erythrocyte changes due to, 4, 199-205 207
 - haemoglobin changes due to, 4, 203 207
 - parental and lifespan, 5, 21-34
 - pulmonary effects of, 4, 264
 - renal effects of, 4, 11-12, 227-228, 229-249, 253-254
- Age factor in prenatal endocrine events, 2, 18-30
- Ageing
- adaptation in, 3, 60-67 71
 - and endocrine glands, 2, 161-162
 - biological approach to, 3, 2-17
 - clinico-pathological tests of, 3, 92-100
 - definition of, 1, 4-14 55-56 57-242 243, 244-245 2, 246-248 249 3, 73 93 131 132 191
 - due to rapid maturation, 3, 194-199
 - effect of environment, 3, 35-37 45-48 171-183 184
 - effect on skull, 1, 209-218
 - emotional changes during, 3, 170-182 184
 - genetic factors in, 1, 26-27 238-241 3, 131-132 133-144 5, 137
 - genetics of
 - in *Drosophila*, 5, 278-280 283
 - twin data in, 3, 131-148
 - horizontal studies of, 3, 95
 - in Africans, 3, 104-114
 - in *Drosophila*, 5, 269-285
 - in leaves, 2, 202-214
 - in red cells, 2, 233-238
 - intelligence changes in, 3, 170-187
 - longitudinal studies of, 3, 95
 - measurement of, 1, 4-15 3, 6-8
 - mental aspects of, 1, 32-52
 - molecular changes in, 5, 129-131

Ageing

- neglected areas in, research on, 1, 173-185
 - nutritional aspects of, 1, 386-193
 - pathological basis of, 1, 16-31
 - performance changes in, 3, 149-169
 - personal measurement of, 1, 5-7
 - psychological aspects of, 1, 209-218
 - physiological approach to, 3, 20-29
 - physiological changes due to in fish, 5, 181-211
 - theory of, 5, 129-131, 269-272, 281, 282, 297
 - use of inbred strains in research into, 3, 115-130
 - use of various animals in research into, 1, 177-181
 - variability in, 3, 32, 33
- Alanine, in elastin, 1, 95-96
- Albatross, lifespan of, 5, 100-103
- Albumin, effect on bees, 5, 235
- Aldosterone, 4, 59-60
- effect on potassium excretion, 4, 183-184 186-192 194, 196-197
 - effect on sodium excretion, 4, 183, 185, 192-194 196
 - effect on sodium/potassium ratio, 4, 184-185 186-187 192-194 196
 - effect on urinary output, 4, 182, 192-194 196
 - excretion in congestive heart failure, 4, 280-292 293 298, 300
 - in pregnancy, 4, 89-90
- Algeria, 2, 100, 101
- Allantoic fluid, 4, 217-218
- Allometry of lifespan, 5, 125
- Aloa sapidissima* fecundity of, 5, 191-192
- Alveolar air, contact with pulmonary blood measurement of, 1, 64-65 66
- Alzheimer's disease, 3, 134-135-136 141 144-146
- Amide N in elastin, 1, 96
- Amisiformes, lifespan of, 5, 222
- Amino acids, effect on bees, 5, 238
- in aorta, 3, 97
 - in cells, 3, 47-49
 - in elastic tissue, 1, 91-94-96, 104
 - in leaves, 2, 203, 206, 207-212
 - in plants, 2, 212
 - in pollen, 5, 237
- Amoeba, growth and development of, 3, 41-42
- Ammonia, excretion, 4, 209-210, 213-215
- in respiratory acidosis, 4, 266
- Antimoonium salts, in metabolism, 4, 209-210
- Ammodramus levis* lifespan of, 3, 12, 13 14-15
- Amphibia, lifespan of, 3, 9
- Amyloid, effect of diet, 5, 79
- Amyloidosis, in mice, 3, 121-122, 125-126 5, 80-81
- Anaemia, erythrocytes in, 4, 199
- in animals, 3, 33-34 36

- Androgens, effect on development of reproductive tract, 2, 10-11
 effect on foetal growth, 2, 133
 produced by ovary 2, 15-16
 Androstosterone 1 128 129 130 131 133 134
 excretion of in old people, 1, 134
 Aneurysm, in old people, 1, 22
 Angelfish, lifespan of 5, 221
 protein metabolism in, 5, 183-185
 Anguina, 1, 82-84, 86
 Angus cattle, lifespan of 5, 60
 Anguilliformes, lifespan of 5, 223
 Anguilluloid, lifespan and size of 5, 152
 Animal populations, control of 5, 296-297
 Animals, ageing process in, 3, 20
 lifespan of (see also under names of animals), 3, 3 8-11
 cause of decrease in, 3, 4-6
 methods of obtaining data, 3, 11-17
 Anions, excretion of 4, 209 210
 in infancy 4, 211 213
 Anser, arteriosclerosis in 5, 109
 Anseriformes, mortality rate of 5 101
 Ant biotica, effect on lifespan, 3, 36
 Antidiuretic hormone, 4, 12, 37 46, 47 53
 53 92, 238-240
 in congestive heart failure, 4, 280
 Antlers, deer (see Deer antlers of)
 Aortic, due to respiratory infection, 4 268
 Aorta, amino acids in 3 97
 calcification of elastic tissue in, 1, 97 98
 calcium in, 3, 97, 98
 degenerative changes in 3 97
 effect of elastase, 3 98 102
 elastin content of, 1, 92 93 94 101
 glycolysis in, 76
 Aortic disease, in cancer cases, 1, 21
 Aortic sclerosis, age incidence of 3, 76
 Aortic tissue, diffusion of solutes through
 1, 69 72 74 76-78
Apis mellifera, 5 247
 Apocrine sweat glands, ageing of 2, 188-201
 control of by endocrine glands, 2, 198
 distribution of 2, 188
 effect of age on 2, 194-198 199
 effect of menstruation on, 2, 196-198
 199-200
 effect of pregnancy 2, 197 198 199-200
 glycogen in 2, 195
 in children 2, 198
 in young adults 2, 190-194
 iron content of, 2, 191 193 195
 lipid content of 2, 191 195
 mitosis in 2, 196 199
 phylogeny of 2, 188
 pigment in, 2, 190-194 195
 ribonucleic acid in 2, 194
 structure of, 2, 189
 Apodiformes, mortality rate of 5, 101
 Apples, ageing in, 2, 206 208, 210
 Aqueous humour concentration of ions in
 4, 25-26 28 29
 Arctic char lifespan of 5, 147
 Arcus senilis, 3, 109
Ardea cinerea lifespan of 5, 99
 Argentine, lifespan and size of, 5, 150
 Arginine, in elastin 2, 96
 Arinadillo, oogenesis in 2, 39, 40
 Arterial spiders, 1, 81 82
 Arteries, age changes in, 1, 53
 cholesterol in 3, 101
 degenerative changes in, 3, 97
 pressure waves in, 3, 69
 Arteriosclerosis, 1, 56 3, 74-77 80, 97 99,
 102, 134 136 137 191, 193-194
 aetiology of, 5, 107-108
 biochemistry of, 1, 28
 brain in 5, 107
 calcification of elastic tissue in 1, 97,
 98 102
 cholesterol in, 1, 78-79, 89, 5, 110-111,
 113
 elastase in, 1, 99
 elastic tissue in 1, 88 89
 in animals, 3, 21, 31 32, 33
 in birds, 5, 106-114
 in cases of cancer 1, 21
 in centenarians, 1, 16
 in dogs, 3, 32 33
 in fish 5, 225
 in mammals, 5, 109
 in monkeys, 5, 108
 incidence of in old people, 1, 18 19 20,
 21 24 25 26
 site of 5, 110
 Ash, in rat body 4, 120-124
 relation to body composition, 4, 118,
 122
 Aspartic acid, in elastin, 1, 91 94 95, 96
 in plants, 2, 212
 Asthma, effect on lung, 1, 65 66
 Barley leaves, protein in, 2, 203-204 205
 respiration in, 2, 206
 Basal metabolic rate, variations with age,
 1 206
 Bass, lifespan of 5, 220 221 223
 Batrachoidiformes, lifespan of, 5, 221
 Bats, lifespan of 5, 97 103
 metabolism and lifespan in, 3, 17
 Bees, ageing in 5, 248
 brain cells in 5, 248
 effect of diet, 5, 254
 effect of protein on, 5, 254
 in tropics, 5, 246
 lifespan of caged 5, 235-239
 factors influencing, 5, 231-246
 in free-flying colony 5, 231-235
 physiological condition of free-flying,
 5, 231 235
 caged 5, 235-239
 yearly life cycle in, 5, 239-240
 Beryculiformes, lifespan of 5, 220
 Bicarbonate, excretion of in respiratory
 excretion, 4, 265-266
 in pancreatic juice 4, 64
 in peroxid saliva, 4, 64

Age

- changes in ketosteroid excretion due to, 4, 91
 - effect of fecundity in fish, 5, 198-200, 201
 - effect on blood volume, 4, 243
 - effect on cells, 4, 199-205
 - effect on deer antler growth, 2, 183-184
 - effect on diuresis, 4, 6-10
 - effect on fecundity in fish, 5, 201
 - effect on homeostasis, 4, 139-153
 - effect on influence of adrenal steroids, 4, 192-194
 - effects on insects, 5, 247-268
 - effect on kidney, 4, 11-12, 227-228, 229-249, 253-254
 - effect on oestrogen excretion, 4, 91
 - effect on renal disease, 4, 250-263
 - effect on reproduction, 5, 181-182
 - effects on reproduction in fish, 5, 186-206
 - effect on starvation, 4, 226
 - effect on water diuresis, 4, 238-240
 - electrolyte changes due to, 4, 241, 311-312
 - erythrocyte changes due to, 4, 199-205, 207
 - haemoglobin changes due to, 4, 203, 207
 - parental and lifespan, 5, 21, 34
 - pulmonary effects of, 4, 264
 - renal effects of, 4, 11, 12, 227-228, 229-249, 253-254
- Age factor in prenatal endocrine events, 2, 18-30**
- Ageing, actuarial measurement of, 1, 7-14**
- adaptation in, 3, 60-67, 71
 - and endocrine glands, 2, 161, 162
 - biological approach to, 3, 2-17
 - clinicopathological tests of, 3, 92, 100
 - definition of, 1, 4-14, 55, 56, 57, 242, 243, 244, 245, 2, 246-248, 249, 3, 73, 93, 131, 132, 191
 - due to rapid maturation, 1, 194-199
 - effect of environment, 3, 35, 37, 45, 48, 171, 183-184
 - effect on skill, 1, 209, 218
 - emotional changes during, 3, 170-182, 184
 - genetic factors in, 1, 26, 27, 238-241, 3, E31, 132-133, 144, 5, 137
- genetics of**
- in *Drosophila*, 5, 278-280, 283
 - twin data in, 3, 131-148
- horizontal studies of, 3, 95**
- in Africans, 3, 104-114
 - in *Drosophila*, 5, 269-285
 - in leaves, 2, 202-214
 - in red cells, 2, 233-238
 - intelligence changes in, 3, 170-187
 - longitudinal studies of, 3, 93
 - measurement of, 1, 4-15, 3, 6-8
 - mental aspects of, 1, 32-52
 - molecular changes in, 5, 129-131

Ageing

- neglected areas in, research on, 1, 173-185
 - nutritional aspects of, 1, 186-193
 - pathological basis of, 1, 16-31
 - performance changes in, 3, 149-169
 - personal measurement of, 1, 5-7
 - psychological aspects of, 1, 209-218
 - physiological approach to, 3, 20-29
 - physiological changes due to in fish, 5, 181-211
 - theory of, 5, 129-131, 269-272, 281, 282, 297
 - use of inbred strains in research into, 3, 115-130
 - use of various animals in research into, 1, 177-181
 - variability in, 3, 32, 33
- Alanine, in elastin, 1, 95, 96**
- Albatross, lifespan of, 5, 100, 103**
- Albumin, effect on bees, 5, 235**
- Aldosterone, 4, 59, 60**
- effect on potassium excretion, 4, 183-184, 186, 192-194, 196-197
 - effect on sodium excretion, 4, 183, 185, 192, 194, 196
 - effect on sodium/potassium ratio, 4, 184-185, 186-187, 192-194, 196
 - effect on urinary output, 4, 182, 192-194, 196
 - excretion in congestive heart failure, 4, 280, 292, 293, 298, 300
 - in pregnancy, 4, 89-90
- Algaria, 2, 100, 101**
- Allantoic fluid, 4, 217, 218**
- Allometry of lifespan, 5, 125**
- Alsea sapidissima* fecundity of, 5, 191-192**
- Alveolar air, contact with pulmonary blood measurement of, 1, 64-65, 66**
- Alzheimer's disease, 3, 134, 135-136, 143, 144, 146**
- Amide N, in elastin, 1, 96**
- Amiiformes, lifespan of, 5, 222**
- Amino acids, effect on bees, 5, 238**
- in aorta, 3, 97
 - in cells, 3, 47, 49
 - in elastic tissue, 1, 91, 94-96, 104
 - in leaves, 2, 203, 206, 207, 212
 - in plants, 2, 212
 - in pollen, 5, 237
- Amoeba, growth and development of, 3, 41-42**
- Ammonia, excretion, 4, 209-210, 213-215**
- in respiratory acidosis, 4, 266
- Ammonium salts, in metabolism, 4, 209, 210**
- Ammotragus lewisii* lifespan of, 3, 12, 13, 14, 15**
- Amphibia, lifespan of, 3, 9**
- Amyloid, effect of diet, 5, 79**
- Amyloidosis, in mice, 3, 121, 122, 125, 126, 5, 80-81**
- Anaemia, erythrocytes in, 4, 199**
- in animals, 3, 33, 34, 36

- Androgens, effect on development of reproductive tract, 2, 10, 11
effect on foetal growth, 2, 173
produced by ovary 2, 15-16
- Androsterone, 1, 122, 129 130, 131 133 134
excretion of in old age, 1 134
- Anemura, in old people, 1 22
- Angelfish, lifespan of 5, 221
protein metabolism in, 5, 183-185
- Angiomata, 1 82-84 86
- Anglo cattle, lifespan of 5, 60
- Anguilliformes, lifespan of, 5, 223
- Anguillidae, lifespan and size of 5 152
- Animal populations, control of 5 296-297
- Animals, ageing process in, 3 20
lifespan of (see also under names of animals) 3 3 8-11
cause of decrease in, 3 4-6
methods of obtaining data, 3 11 17
- Ascorbic acid, excretion of 4, 209 210
in infancy 4, 211 213
- Ascaris, arteriosclerosis in, 5, 109
- Ascariformes, mortality rate of 5, 101
- Amblyopia, effect on lifespan, 3 36
- Antidiuretic hormone, 4, 12, 37 46 47 53
55 92, 238-240
in congestive heart failure, 4, 280
- Antlers, deer (see Deer antlers of)
- America, due to respiratory infection, 4, 268
- Aorta, amino acids in, 3 97
calcification of elastic tissue in, 1 97 98
calcium in, 3, 97 98
degenerative changes in, 3, 97
effect of elastase, 3 98, 102
elastin content of 1, 92-93 94 101
glycolysis in, 1 76
- Aortic disease, in cancer cases, 1, 21
- Aortic sclerosis, age incidence of 3, 76
- Aortic tissue, diffusion of solutes through, 1 69 72 74 76-78
- Apis mellifera, 5, 247
- Apocrine sweat glands, ageing of 2, 188-201
control of by endocrine glands, 2, 198
distribution of 2, 188
effect of age on, 2, 194-198 199
effect of menstruation on, 2, 196-198 199-200
effect of pregnancy 2, 197 198 199-200
phylogeny in, 2, 193
in children, 2, 198
in young adults, 2, 190-194
iron content of 2, 191 193 195
lipid content of 2, 191 193 195
mucous in, 2, 196 199
phylogeny of 2, 188
pigment in, 2, 190-194 195
ribonucleic acid in, 2, 194
structure of 2, 189
- Apodiformes, mortality rate of 5, 101
- Apples, ageing in, 2, 206, 208 210
- Aqueous humour, concentration of ions in 4, 25-26, 28 29
- Arctic char lifespan of 5, 147
- Arcus senilis, 3, 109
- Ardea cinerea, lifespan of 5, 99
- Argentine, lifespan and size of 5, 150
- Argonase, in elastin, 1, 96
- Armadillo oögenesis in 2, 39 40
- Arterial spasm, 1, 81, 82
- Arteries, age changes in, 1, 51
cholesterol in, 3, 101
degenerative changes in, 3, 97
pressure waves in, 3, 69
- Arteriosclerosis, 1, 56 3 74-77 80 97 99, 102, 134 136, 137 191 193-194
aetiology of 5, 107-108
biochemistry of 1, 28
brain in, 5, 107
calcification of elastic tissue in, 1, 97, 98, 102
cholesterol in 1, 78-79 89 5, 110-111 113
elastase in, 1, 99
elastic tissue in 1, 88 89
in animals, 3, 23 31 32, 33
in birds, 5 106-114
in cases of cancer, 1, 21
in centenarians 1, 16
in dogs, 3 32, 33
in fish 5, 225
in mammals, 5, 109
in monkeys, 5, 108
incidence of in old people, 1, 18 19 20 21 24, 25 26
size of 5, 110
- Ash, in rat body 4 120-124
relation to body composition 4, 118, 122
- Aspartic acid, in elastin, 1, 91 94 95, 96
in plants, 2, 212
- Asthma, effect on lung, 1, 65 66
- Barley leaves, protein in 2, 203-204 205
respiration in, 2, 206
- Basal metabolic rate, variations with age, 1, 206
- Bass, lifespan of 5, 220 221, 223
- Batrachoidiformes, lifespan of 5, 221
- Bats, lifespan of 5, 97 103
metabolism and lifespan in, 3, 27
- Bees, ageing in, 5, 248
brain cells in, 5 248
effect of diet, 5 254
effect of protein on, 5, 254
in tropics 5 246
lifespan of caged 5 235-239
factors influencing, 5 231 246
in free-flying colony 5, 231-235
physiological condition of free-flying 5, 231 235
caged 5 235-239
yearly life cycle in 5, 239-240
- Beryciformes, lifespan of 5, 220
- Bicarbonate, excretion of in respiratory acidosis, 4 265-266
in pancreatic juice, 4, 64
in parotid saliva, 4, 64

- Birds, ageing in 3, 9
arteriosclerosis in 5, 106-114
expectation of life in 1, 4
in research on ageing 1, 177
lifespan of, 3, 9 17 37
in captivity, 5, 103
in Nature, 5, 90-105
metabolism and lifespan in, 3, 28
Bison, lifespan of, 5, 105
Blackfish, lifespan of 5, 221
Black pied cattle, lifespan of, 5, 60
Bladder, cancer of in old people, 1, 21
Blatella germanica, in research on ageing 1, 174
Blennioides, lifespan and size of 5, 152
Blennius pholis growth of 5, 156, 157, 158
lifespan and size of 5, 152
Blenny (see *Blennius pholis*)
Blood, ventilation of 1, 62, 63 66 68
Blood-brain barrier, 4, 26
Blood pressure, age changes in 3, 32 33 64
changes in 3, 6
Blood supply to brain, in old people 1, 51
Blood volume, effect of age 4, 243
Blue-head, lifespan of 5, 221
Blue-striped grunt, lifespan of, 5, 221
Body composition, effect of protein and mineral intake on 4 116-138
Body weight, relationship to lifespan 5, 115-139
Bone, magnesium in 4, 309
molecular changes in 3, 47 48
Dicotyles tragocamelus lifespan of 3, 12 13
Bowfin, lifespan of 5, 222
Brain, blood supply to in old people 1, 51
changes in in Alzheimer's disease 3, 135-136 143-144 146
in old age 1, 34 35 36 49 51 3, 145 146 147
in Pick's disease 3, 135 136 143 144 146
in arteriosclerosis 5, 107
internal environment of 5, 133
weight of relationship with lifespan 5 115-139
Brain cells, in bees, 5, 248
Breast cancer, in cattle 5, 71
in centenarians, 1, 16
in mice 3, 119 120
Bronchiectasis, in aged rats 1, 178 179
Bronchitis, and emphysema 1, 65 66
Bull frog, metabolism and lifespan 3, 26
Bullhead, effect of diet on 5, 169
lifespan of 5, 152, 223
size of 5, 152
survival curves of 5, 143 145
Bulls, causes of death in 5, 65
lifespan of 5, 64-65
Barbot, lifespan of 5, 223
Buteo buteo lifespan of, 5, 99
Butterflies, 3, 25
Butterfly fish, lifespan of 5, 121
Buzzards, lifespan of 5, 99
Calcium, absorption of, 1, 110, 111-114 119-120, 124-125
effect of diet on, 4, 120, 121, 127-128 132, 138
in aorta, 3, 97, 98
in body of rat, 4, 120, 121, 127-128, 132, 138
in elastin, 1, 97-98, 104, 105
in foetal urine, 4, 218
in placenta, 2, 110
requirements of, 3, 109 120-122
Calcium balance studies, 1, 114-118
Calcium binding age changes in, 3 67
Calcium metabolism, in old age 1, 109-125
in osteoporosis, 1, 109, 110, 116-118, 121, 122 123, 125
in rats, 1, 111-114, 124-125
Callosymoldes, lifespan and size of 5, 152
Callionymus lyra mortality rate of, 5, 146
survival curves of, 5, 143, 145
Cancer, (see Carcinoma)
Cancer eye, in cattle, 5, 71
Canis lifespan of 3, 12-13 14 17 5, 134
Capelin, lifespan and size of, 5, 150
mortality rate of 5, 146
Capreolus capreolus lifespan of, 5, 92 94
Carbohydrate, in pollen 5, 237, 238
Carbohydrate metabolism, endocrine factors in 2, 24-25
Carbon dioxide, diffusion of through aortic tissue 1, 72-74 77
diffusion through tentorium cerebelli 1, 74-75
Carbon dioxide production, age changes in 3, 77 84-90
Carbonic anhydrase, 4, 218 221
control of urinary pH 4, 210
Carcinoma, arteriosclerosis in cases of, 1, 21
in Africans 3, 104 106, 113
in animals 3, 31
in fish 5, 226
in inbred strains, 3, 117 118 119 120 121
incidence of in old people 1, 18 19 20 21 24 25-26
sites of in old people 1 21-22
Cardiac output, 3, 84-86 87 191
effect on kidneys, 4, 234 248, 267
in congestive failure 4, 272, 276
Cardiac stroke index, age changes in 3, 87 88
Caribou lifespan of 5, 92 94
Castration, 4 227
effects of 2, 10
effect on adrenals, 4 197 198
Cat lifetime energy expenditure of 5, 127
lifespan of 5, 134
Catfish, lifespan and size of 5, 154 220 223
Cattle, breeding of 5 57 58
lifespan of 5, 57-65 70 71
Cavalier lesions, 1, 84 86
Cavy, lifespan of 3, 12 13

- Cell(s), age changes n, 1 52 53 54 55
 2, 250 3, 39-50 4 199-205
 changes n, 3, 43-44
 cold storage of 2, 215 216
 effect of on onment on, 3 45
 effect of nutr tion on, 1 191
 effect of temperature on, 5 281
 electro yes and water n, 4, 15-35
 electro y e transfer n, 4, 19
 enzymes in, 3 47 48
 function of 3, 41
 in test s, 2, 86-99
 lifespan of 2, 216 227 3 5
 metabolism, 2, 216 217
 mutation in 3, 43 45
 nuclear transplants on in, 3, 46
 nucleic acids n 3, 47 48
 nucleus of 2, 239-240 241
 osmo ic equilibrium of 4, 18
 oxygen in metabolism, 2, 243
 proliferation of 3 41-42, 46
 proteins in 3, 48 49
 replacement of 3 4 5 6 8
 Cell membrane, permeab y of 4, 16-31
 Cell respiration, relationsh p w th pro ein
 metabolism, 2, 207 208
 Centenarians, 3 93
 accuracy of age of 5 13
 emphysema n, 1 16
 memory in, 1 25
 mental state of 1 25
 pathological lesions n, 1 16-17
 Central nervous system, control of vital
 functions by 5, 128-129
 Centrarchidae, protein metabolism n, 5
 182-183
 Cerebral blood supply in old poop e, 1 51
 Cerebral hypoxia, n congestive heart
 failure, 4 286
 Cerebral vascular disease, n cases of
 cancer 1 21
 n old people, 1 22
 Cerebrospinal fluid, concentration of ons
 n, 4, 25-26
 Cer us elaphus lifespan of 5, 92 94
 Chaffinch, lifespan of 3 9
 Char fecund y of 5 191 192
 lifespan and size of 5 152
 Characin, i lifespan of 5, 224
 Charadriiformes, morta y rate of 5, 101
 Cherry angiomas, 1 82-84 86
 Chickens, arterioscle osis n, 5, 110 113
 Children, diet for spastic, 1 183
 heights and weights of 1 195 201
 malnir uon in 1 195
 water n body of, 4, 101-106
 Chiroptera gliridex lifespan of 5 96
 Chlorides, effect of diet on, 4, 1.0 121
 1 6 132
 c tre ion of n congestive heart failure,
 4, 2 6 277 278 284-85
 n babies urine, 4, 211
 n body of rat, 4, 1.0, 121 126, 132
 n erythrocytes, 4, 203
 Chlorides
 in foetal urine, 4 217
 n sweat, 4, 64 74
 in tears, 4 64 71
 loss of during labour 4 90
 Chlorophyll, in nasturtium 2, 203
 Cholesterol, 1 126 127
 in art ology of arteriosclerosis, 5, 110-
 111 113
 n arteries, 3, 101
 n arteriosclerosis, 1, 78-79 89 5 110-
 111 113
 in elastin 1 97 98
 n placenta, 2, 122
 loss of from red cells, 2, 218 219 220
 Cholesterol metabolism 3 191 193-194
 and ageing, 3, 133
 fa ty acids in 3 193-194
 Cholinesterases, age activ ty of 5 247
 Chorioallantoic membrane 4 218
 Chorion, membranous, n goat, 2, 151
 153 154, 156-158
 Chrysops lifespan of 5 103
 Chub, lifespan of 5, 150 221
 size of 5, 150
 Chymotrypsin, 3 101
 Ciconiiformes, mortal ty rate of 5 101
 Circulation, age changes in, 3 77 84-90
 effec s of deficiency of water 4, 160 163
 nervous control of n foetus 2, 29
 Cirrhosis of h er 3 107 108 113
 Cisco lifespan and size of 5 150
 C te us p gmaeus lifespan of 5 97
 C tre acid, excretion of 4, 217 218 221
 222
 Cladocera, 1 30
 Cleft palates, p oduced by cort sone 2,
 18-19
 Clinicopathological tests of ageing, 3 92
 100
 Clupea harengus growth of 5, 156, 157
 158
 Clupea pallas fecund ty of 5 196-197
 Clupea p lehard s 3 26
 Clupeiformes, lifespan of 5 220 222
 Clupeoides, lifespan and growth in 5 160-
 166
 lifespan and size of 5, 143
 Clupeoids, survi al curves of 5 143, 145
 Coalfish, lifespan and size of 5, 148
 Coates knifefish, lifespan of 5 224
 Cobalt deficiency 3 188-190
 Cockroaches, effect of diet on 5, 253-254
 n research on ageing, 1 174 175
 lifespan of 5 253-254
 Cod, lifespan and growth of 5 160-166
 lifespan and size of 5 148
 Cold effect on ce l 4 24
 effect on red cells, 2, 224-229 236-237
 244
 Collagen, 3 96, 97 98
 age changes in, 3 48 65 66 68 71
 contrac ion of 3, 66, 70
 in elastin, 1 91

- Birds, ageing in, 3, 9
 arteriosclerosis in 5, 106-114
 expectation of life in, 1, 4
 in research on ageing 1, 177
 lifespan of, 3, 9 17 37
 in captivity, 5, 103
 in Nature, 5, 90-105
 metabolism and lifespan in, 3, 28
 Bison, lifespan of 5, 105
 Blackfish, lifespan of, 5, 221
 Black pied cattle, lifespan of, 5, 60
 Bladder, cancer of in old people 1, 21
Blatella germanica in research on ageing 1, 174
 Blennio, lifespan and size of 5, 152
Blennius pholis growth of 5, 156, 157, 158
 lifespan and size of 5, 152
 Bienny (see *Blennius pholis*)
 Blood, ventilation of 1, 62, 63 66, 68
 Blood brain barrier, 4, 26
 Blood pressure, age changes in, 3, 32, 33 64
 changes in 3, 6
 Blood supply to brain, in old people, 1, 51
 Blood volume, effect of age, 4, 243
 Blue-head, lifespan of 5, 221
 Blue-striped grunt, lifespan of, 5, 221
 Body composition, effect of protein and mineral intake on 4, 116-138
 Body weight, relationship to lifespan 5, 115-139
 Bone, magnesium in 4, 309
 molecular changes in 3, 47 48
Dicotyles tragocamelus lifespan of 3, 12, 13
 Bowfin, lifespan of 5, 222
 Brain, blood supply to in old people, 1, 51
 changes in in Alzheimer's disease 3, 135-136 143 144 146
 in old age 1, 34 35 36 49 51 3, 145 146 147
 in Pick's disease 3, 135 136 143 144 146
 in arteriosclerosis 5, 107
 internal environment of 5, 133
 weight of relationship with lifespan 5, 115-139
 Brain cells, in bees, 5, 248
 Breast cancer, in cattle 5, 71
 in centenarians, 1, 16
 in mice, 3, 119 120
 Bronchiectasis, in aged rats, 1, 178 179
 Bronchitis, and emphysema 1, 65 66
 Bull frog, metabolism and lifespan 3, 26
 Bullhead, effect of diet on, 5, 167
 lifespan of 5, 152, 223
 size of 5, 152
 survival curves of 5, 143 145
 Bulls, causes of death in 5, 65
 lifespan of 5, 64-65
 Burbot, lifespan of 5, 223
Buteo buteo, lifespan of 5, 99
 Butterflies, 3, 25
 Butterfly fish, lifespan of, 5, 121
 Buzzards, lifespan of, 5, 99
 Calcium, absorption of, 1, 110, 111-114, 119-120, 124-125
 effect of diet on, 4, 120, 121, 127-128 132, 138
 in aorta, 3, 97, 98
 in body of rat, 4, 120, 121, 127-128, 132, 138
 in elastin 3, 97-98, 104, 105
 in foetal urine, 4, 218
 in placenta, 2, 110
 requirements of, 1, 109 120-122
 Calcium balance studies, 1, 114-118
 Calcium binding age changes in, 3, 67
 Calcium metabolism, in old age 1, 109-125
 in osteoporosis, 1, 109, 110, 116-118, 121, 122 123 125
 in rats, 1, 111-114, 124-125
 Callionymoides, lifespan and size of 5, 152
Callionymus lyra mortality rate of 5, 146
 survival curves of, 5, 143, 145
 Cancer, (see Carcinoma)
 Cancer eye, in cattle 5, 71
 Cattle lifespan of 3, 12-13 14 17 5, 134
 Capelin, lifespan and size of, 5, 150
 mortality rate of 5, 146
Capreolus capreolus lifespan of, 5, 92 94
 Carbohydrate, in pollen 5, 237, 238
 Carbohydrate metabolism, endocrine factors in 2, 24-25
 Carbon dioxide, diffusion of through aortic tissue 1, 72 74 77
 diffusion through tentorium cerebelli 1, 74-75
 Carbon dioxide production, age changes in 3, 77 84-90
 Carbonic anhydrase, 4, 218 223
 control of urinary pH 4, 210
 Carcinoma, arteriosclerosis in cases of 1, 23
 in Africans 3, 104 106 113
 in animals 3, 31
 in fish 5, 226
 in inbred strains 3, 117 118 119 120 121
 incidence of in old people 1, 18 19 20 21 24 25 26
 sites of in old people 1, 21 22
 Cardiac output, 3, 84 86 87 191
 effect on kidneys 4, 234 248 267
 in congestive failure 4, 272 276
 Cardiac stroke index, age changes in 3, 87 88
 Caribou, lifespan of 5, 92 94
 Castration, 4, 227
 effects of 2, 10
 effect on adrenals 4, 197 198
 Cat lifetime energy expenditure of 5, 127
 lifespan of 5, 134
 Catfish, lifespan and size of 5, 154 220 223
 Cattle, breeding of 5, 57 58
 lifespan of 5, 57 65 70 71
 Cystic lesions, 1, 84 86
 Caty, lifespan of 5, 12 13

Deer

- antlers of (continued)
- endocrine factors in growth of 2, 179-181
- growth cycle of 2, 176-187
- mechanism of growth 2, 176-178
- radio-phosphorus uptake in 2, 177-178
- shedding of 2, 179, 181, 184 211
- cyclic gonadal changes in, 2, 179
- growth in 1, 205-206
- lifespan of 3 12 5, 91 94
- Dehydration, effect on water intake, 4, 4
- in elderly 1 203
- in labour 4, 94, 95
- Dehydration reaction, 4, 38-39 47
- Dehydroepiandrosterone, 1 127 128
- Demeritis, genetics of 3 137 147
- senile, 1 35 36 44 45 46 214
- de Morgan's spots, 1 82-84 86
- 11 Deoxycortisol, 1 127, 128
- Deoxyribose nucleic acid, 3, 47 48 49
- Diabetes insipidus, causing loss of water 4, 39 42-43
- Diarrhoea, causing hypernatraemia, 4 58
- Dibenzamine, effect on kidney 4 281 282
- Diet, effect on amyloid 5, 79
- effect on bees, 5 254
- effect on body composition, 4, 117 138
- effect on cockroach, 5, 253-254
- effect on electrolytes, 4, 116-138
- effect on fertility 5 34
- effect on fish, 5 178 215-216
- effect on furs, 5, 249-255
- effect on growth 4 116-138 5 84-85 177 178 254-255
- effect on homeostasis, 4, 143-144
- effect on lifespan 1 30 5 78 83-85 87 88 169 177 178 249-255 265-267 268, 282
- effect on mice, 5 79-80
- effect on mosquito 5 255
- effect on rat, 5, 78 83-85 87 88 231 252, 254
- effect on sexual maturity 5, 84-85
- effect on trout, 5, 253 254
- effect on wasps, 5 255
- protein 5, 252-254
- Diffusion coefficients of solutes for membranes, 1 69-79
- Digestive disease incidence of in old people, 1 20
- Dingoes, lifespan of 3, 12
- Dipodomys heermanni* lifespan of 5 96
- Disease effect on lifespan 3 31 32 5 72-89
- Diuretics, effect of adrenal ne, 4, 9 14
- effect of age, 4, 6-10 238-240
- effect of cortisone, 4 13
- effect of hypoxia, 4 8
- effect of p-tyrosine 4, 7-8 11
- effect on adrenal glands, 4, 13
- in congestive heart failure, 4, 272-273 275

- DOCA (deoxycorticosterone acetate), effect on foetus, 2, 24
- Doctor fish, lifespan of 5, 221
- Dog(s), in research on ageing 1 182
- lifespan of 3, 12, 13 14, 17 5, 134
- lifetime energy expenditure of 5, 127
- oogenesis in 2, 43
- Dog snapper, lifespan of 5 221
- Dolichotis patagonica* lifespan of, 3, 12, 13
- Domestication, effects of 3, 15 37
- Dragonet, lifespan and size of 5, 152
- mortality rate of 5 146
- survival curves of 5, 143 145
- Drosophila* effect of heredity on lifespan 1, 239-241
- Drosophila melanogaster* effect of temperature on lifespan 3, 24
- Drosophila subobscura* lifespan of 5, 262, 266
- rate of ageing in 5, 269-285
- Drum, lifespan of 5 221
- Ducks, arteriosclerosis in, 5, 109
- Dwarf top-minnow reproduction and senescence in, 5, 189
- Education, effect on performance 3 159-160
- Eel, lifespan of, 5, 152, 223
- size of, 5, 152
- natural death in, 5, 174
- Eggs, effect on nutrition 1 205
- Egg production, variation with age, 3, 21
- Elastase 1 98-101 107 3, 97-98 101-103 136
- in arteriosclerosis, 1, 99
- in fish 1 99
- in pancreas 1 98 99 100
- preparation of 3 101
- production of 3 45
- tracer studies with, 1 100-101
- Elastic tissue, ageing of, 1, 88-108 3, 65, 66
- amino acids in 1 91 94-96 104
- in atherosclerosis 1 88 89
- in skin, 1 100-102 105 106 107 108
- preparation of, 1, 90-91
- Elastin, calcium content of 1 97-98 104 105
- cholesterol content of 1 97 98
- in aorta 1 92 93 94 101
- in pulmonary artery 1 93-94
- polysaccharides in, 1 104 107
- preparation of 1 90-91 104
- Elastosis, 3 96, 97
- senile, 1, 101 103 106-108
- Electric catfish, lifespan of 5 224
- Electric eel, lifespan of 5, 224
- Electrolytes (see also under Sodium potassium, etc.)
- cellular aspects of 4, 15-35
- changes in due to age 4, 241 311 312
- deprivation of 4 144
- effect of diet, 4, 116-138

- Collagen**
 in placenta, 2, 146
 in scar tissue, 3, 70
Collagen fibres, 1, 88, 106, 107, 108
Colon, cancer of in old people, 1, 21
Columbiformes, mortality rate of, 5, 101
Comparative age studies, 3, 1-38
 clinicopathological tests, 3, 92-100
Compensatory adjustment in ageing, 1, 25, 27, 41, 42, 43, 46, 47
Congestive heart failure, aldosterone excretion in, 4, 280, 292-293, 298, 300
 cerebral hypoxia in, 4, 286
 humoral factors, 4, 279-288
 neural factors, 4, 279-288
 renal changes in, 4, 275-279
 renal function in, 4, 271-275
 salt and water retention in, 4, 288-293
 water and electrolyte metabolism in, 4, 271-300
Connective tissue, age changes in, 3, 65
 water and electrolytes in, 4, 27
***Coregonus clupeaformis*, survival curves of**, 5, 143, 144
Cormorants, arteriosclerosis in, 5, 109
Coronary disease, in cancer cases, 1, 21, 22
Coronary sclerosis, age incidence of, 3, 74, 75
***Coronella laevis*, fertility of**, 3, 21
***Cor pulmonale*, renal function in**, 4, 266-267
Corpus luteum, effect on parturition, 2, 79, 85
 effect on placenta, 2, 84
 effect on pregnancy, 2, 78, 79, 84
 effect on uterus, 2, 78-79
 growth rate of, 2, 79, 80
 of guinea pig, 2, 69-85
 in guinea pigs, growth rate of, 2, 73, 75
 in pregnancy, 2, 74, 75, 76, 84
 ovulation changes in, 2, 71-72, 83, 84
 lifespan of, 2, 80-82
Cortexone, effect on potassium excretion, 4, 174-175
 effect on sodium excretion, 4, 174, 175, 177
 effect on water loss, 4, 174, 175
Corticosterone, administration of in old age, 1, 134-136
Cortin, excretion of, in elderly and schizophrenics, 3, 221-222, 223-236
Cortisol, 1, 127, 128
 administration of in old age, 1, 134-136
 effect on potassium excretion, 4, 188, 189, 192-194, 196
 effect on sodium excretion, 4, 187-188, 189, 192-194, 196
 effect on sodium/potassium ratio, 4, 190-192, 193-194, 196
 effect on urinary output, 4, 187, 188, 192-194, 196
Cortisone, effect on adrenal glands, 4, 175-176
 effect on diuresis, 4, 13
Cortisone
 effect on hair, 2, 175
 effect on placenta, 2, 141
 effect on postnatal growth, 2, 168-171
 effect on potassium excretion, 4, 171, 172, 176, 178
 effect on sodium excretion, 4, 171, 172, 173, 176, 178
 effect on water loss, 4, 171, 172
Cottoidel, lifespan and size of, 5, 152
***Cottus gobio*, survival curves of**, 5, 143, 145
Cough, effect on lung, 1, 65
Cows, average age of different breeds, 5, 59
 cause of death, 5, 63-64
 lifespan of, 5, 58-64, 70
 lifetime energy expenditure of, 5, 127
Cowfish, lifespan of, 5, 221
Creatinine excretion, 4, 249
 in elderly and schizophrenics, 1, 221-222, 223-236
Creatinuria, in rats, 5, 83
***Cristivomer namaycush*, mortality rates of**, 5, 145
Croaking gourami, lifespan of, 5, 224
Cross linking, 3, 66, 68, 69
 in carcinogenesis, 3, 68
Cross-sectional studies, 3, 158-159, 171-172, 173, 174, 179, 186
Crystalloids of Reinke, 2, 92, 94, 95
Cunner, lifespan of, 5, 221
Cyprinids, metabolism of, 5, 169
Cypriniformes, lifespan of, 5, 220, 222, 224
Cyprinodontiformes, lifespan of, 5, 152, 224
 size of, 5, 152
Cyprinoidel, lifespan and size of, 5, 152
Cystine, in elastin, 1, 96
Dab, fecundity in, 5, 192, 200-202
Dace, lifespan of, 5, 223
Daphnia, effect of metabolic rate on lifespan, 3, 24
 effect of nutrition on lifespan, 3, 24-25
***Dasyatis akajel*, lifespan and growth of**, 5, 163
Dasyatis, oögenesis in, 2, 56
Deaths, accidental, 5, 17
 accuracy of age at, 5, 12-13
 age at, 3, 7
Death curves, 5, 6-9, 15, 17, 286-296
 of horses, 5, 56
Death rate, anticipated, 5, 4, 5, 7, 12, 15
 formula for, 1, 8
 laws governing, 5, 2-4
 senescent, 5, 4, 5, 6, 7, 10, 11, 12
Decarboxylic amino acids, in elastin, 1, 94, 95, 103
Deer, antlers of absence of, 2, 186
 blood supply of, 2, 177, 185
 effect of age on, 2, 183-184
 effect of nutrition on, 2, 184
 effect of testosterone on, 2, 179-180, 186
 enervation of, 2, 178, 185-186

Deer

- antlers of (*continued*)
- endocrine factors in growth of 2, 179-181
- growth cycle of 2, 176-187
- mechanism of growth 2, 176-178
- radio-phosphorus uptake in, 2, 177-178
- shedding of 2, 179 181 184 211
- cyclic gonadal changes in, 2, 179
- growth in, 1 205-206
- lifespan of 3 12 5, 91 94
- Dehydration, effect on water intake 4, 4
- in elderly 1, 207
- in labour 4, 94 95
- Dehydration reactions, 4, 38-39 47
- Dehydroepiandrosterone, 1, 127 128
- Dementia, genetics of 3 137 147
- senile, 1 35 36 44 45 46 214
- de Morgan's spots, 2 82-84 86
- 11 Deoxycortisol, 1, 127 128
- Deoxyribose nucleic acid, 3, 47 48, 49
- Diabetes insipidus, causing loss of water 4, 39 42-43
- Diarrhoea, causing hypernatraemia, 4 58
- Dibenzamine, effect on kidney 4 281 282
- Diet, effect on amyloid, 5 79
- effect on bees, 5, 254
- effect on body composition 4, 117 138
- effect on cockroach, 5 253-254
- effect on electrolytes 4 116-138
- effect on fertility 5, 34
- effect on fish, 5 178 215-216
- effect on flies, 5, 249-255
- effect on growth 4, 116-138 5, 84-85 177 178 254-255
- effect on homeostasis, 4, 143-144
- effect on lifespan 1 30 5 78 83-85 87 88 169 177 178 249-255 265-267 268 282
- effect on mice, 5, 79-80
- effect on mosquito 5 255
- effect on rat, 5, 78 83-85 87 88 251 252, 254
- effect on sexual maturity 5, 84-85
- effect on trout, 5 253 254
- effect on wasps, 5 255
- protein in 5, 252 254
- Diffusion coefficients of solutes for membranes, 1 69-79
- Digestive disease incidence of in old people, 1 20
- Dingos, lifespan of 3, 12
- Dipodomys heermanni*, lifespan of 5 96
- Disease effect on lifespan, 3 31 32 5 72-89
- Diuresis, effect of adrenal ne, 4 9 14
- effect of age, 4, 6-10 238-240
- effect of cortisone, 4, 13
- effect of hypoxia, 4, 8
- effect of pituitary 4, 7 2 11
- effect on adrenal glands, 4, 13
- in congestive heart failure, 4, 272 273 275

- DOCA (deoxycorticosterone acetate), effect on foetus, 2, 24
- Doctor fish, lifespan of 5, 221
- Dogs, in research on ageing 1 182
- lifespan of 3, 12, 13 14 17 5, 834
- lifetime energy expenditure of 5, 127
- oogenesis in, 2, 43
- Dog snapper lifespan of 5, 221
- Dolichopus patagonus* lifespan of 3, 12, 13
- Domestication, effects of 3, 15 37
- Dragonet, lifespan and size of 5, 152
- mortality rate of 5 146
- survival curves of 5, 143, 145
- Drosophila* effect of heredity on lifespan 1, 239-241
- Drosophila melanogaster* effect of temperature on lifespan, 3 24
- Drosophila subobscura* lifespan of, 5, 262, 266
- rate of ageing in 5, 269-285
- Drum lifespan of 5, 221
- Ducks, arteriosclerosis in, 5, 109
- Dwarf top-munnow reproduction and senescence in, 5, 189
- Education, effect on performance, 3, 159-160
- Eel, lifespan of 5 152, 223
- size of 5 152
- natural death in 5, 174
- Eggs, effect on nutrition 1, 205
- Egg production, variation with age, 3, 21
- Elastase, 1, 98-101 107 3 97-98 101-103 136
- in arteriosclerosis 1, 99
- in fish, 1 99
- in pancreas, 1 98 99 100
- preparation of 3, 101
- production of 3 45
- tracer studies with, 1, 100-101
- Elastic tissue ageing of 1 88-108 3, 65 66
- amino acids in 1 91 94-96 104
- in arteriosclerosis 1 88 89
- in skin, 1, 100-102, 103 106 107 108
- preparation of 1 90-91
- Elastin, calcium content of 1 97 98 104 105
- cholesterol content of 1 97-98
- in aorta, 1 92 93 94 101
- in pulmonary artery 1 93-94
- polysaccharides in 1 104 107
- preparation of 1, 90-91 104
- Elastosis, 3 96 97
- senile, 1, 101 103 106-108
- Electric eel, lifespan of 5 224
- Electrolytes (*see also under Sodium* potassium, etc.)
- cellular aspects of 4 15-35
- changes in due to age, 4, 241 311 312
- deprivation of 4, 144
- effect of diet, 4, 116-138

- Electrolytes**
 effect of hormones, 4, 313 314
 effect of hypercapnia 4 265
 effect on mineral content of body 4 125
 effect on prote n body content 4 125
 excret on of n elderly schizophren cs, 1 223 237
 response to adrenal steroids, 4 180-194 196-198
 glandular secret on of 4 62 77
 hormonal aspects of 4 78-98
 n congestive heart failure 4 271 300
 n muscle, 4 164
 in parenteral fluid therapy 4 146-148
 n pregnancy 4 88 90
 metabolism in infancy 4 154-164
 regulat on of by kidney 4 229 249
 total exchangeable in body 4 108
- Elephants, lifespan of** 1 242
- Emotion, changes n w th age, 3** 170-182 184
- Emphysema** aetiology of 1 65-66
 antispasmodics n 1 67
 bronchitis and 1 65 66
 diffusion capacity n 1 64-65 66
 in centenarians, 1 16
 pulmonary ventilation n 1 62 63
 sex distribution n 1 68
 vital capacity in 1 58 59 60
- Endocrine organs, age changes n** 2, 161 162 3 128-129
 control of apocrine sweat glands by 2, 198
- Endometrium** pregnancy changes n 2, 115
- Environment** effects of 3 171
 effect on age ng, 3 35 37 45 48 145 148 171 183-184
 effect of lifespan 5 167 168 209
 effect on onset of decline 5 86-87
- Enzymes, in cells, 3** 47 48
 n rat placenta 2, 107 108
 n red cells 2 235 241
- Enzyme production, 3** 44 45
- Eosinophils, levels of variations w th age** 1 223 231 232
- Fibredrine** n emphysema 1 67
- Epinephalus guatus** protein metabolism n 5 183 184
- Erythema palmar** 1 82
- Erythrocytes, electrolytes and water n** 4, 17 21 199 208
 n foetus, 4 204 205 206
 in sheep 4 200-203 204 206
- Feces, effect of nutrit on on** 2, 184
- Experience** effect of on performance 3 156-158
- Extracellular fluid equilibrium w th plasma** 4 15-16
 volume of changes due to age 4 244
- Eyes, changes w th age** 1 214 3, 109 195
 water content of 4, 28, 29
- Eyesight** 3 182 183
- Falconiformes, mortality rate of** 5, 101
- Fats, in body** 4, 113 114 115 129 132
 in pollen 5 237
 in rat body 4 119
 storage in bees 5, 237 238 239
- Fat body in bees, 5, 233 235 237, 238** 244
- Fatigue in old people** 5 150, 151
- Fatty acids, in cholesterol metabolism, 3,** 193 194
- Fecundity** variation of in fish 5 191-192
- Female longevity n** 3 30
- Fertility** effect of age on 3 20-22
 effect of parental age on 5, 56
- Fibrin** n placenta 2, 110
- Fibrinoid, n placenta, 2,** 110
- Finch** lifespan of 5 99 103
- Fish (see also under common names)**
 changes in due to ageing 5 218
 effect of diet on 5 167
 effect of fat diet on 5 215-216
 effect of growth and size on lifespan 5 147 159
 effect of toxic substances on 5, 177
 egg counting in 5, 192 193
 elastase n 1 99
 fecundity n relat on to age in 5 186-206
 fertility of 3 22
 growth of utilization of prote n n 5 182 186
 growth and senescence in 5 217
 growth rate and lifespan 5 227 229
 n nutritional research 1 174 175
 infectious disease 5 213 214 218
 lifespan of 1 28 29 3 9 15 16
 characteristics of long 5, 217 218
 n captivity 5 212 230
 n different species 5 219-224
 n Nature 5, 142 160
 lipid metabolism n 5 227
 metabolic disease n 5, 216
 metabolism of 5, 169-170
 metabolism and lifespan in 3, 25- 6
 natural death and reproduction in 5, 170-174
 natural mortality of 5 147 147
 neoplasia in 5, 216
 nur on n 5 215
 ovaries of 5 193
 parasites n 5 213 216
 physiological changes due to ageing 5, 181 211
 protein utilization in 5 210
 relat onal p of age mortality and growth in 5 160-166
 survival curves of 5, 143 147
 variation n fecundity of 5 191 192
- Flamingoes, effect of diet on** 5 112
- Flexure lines, 1** 17 13
- Flies (see also Houseflies)**
 lifespan of 5 103
- Flounder** lifespan and size of 5 150

- Fluids, metabolic disturbances, reasons for 4 134-135
- Foetal gigantism, 2, 112, 162, 164 166 167 171
- Foetus, acid-base balance in, 4, 217-219
blood vessels of radio-potassium in, 2, 160
decapitation of effects of 2, 12, 0-30
effect of cortisone on 2, 167 175
effect of DOCA on, 2, 24
effect of gonadotrophic hormone on 2, 28
effect of growth hormone on 2, 161 167 171 173-175
effect of testosterone on, 2, 173
endocrine system in 2, 18-30
haemoglobin in 4, 203
modification of growth of by growth hormone and cortisone 2, 161 175
urine in 4 217
weight of 2, 124 125 127
effect of growth hormone, 2, 164-165
- Follicles, atresia of, 2, 59-65
changes of in guinea pigs, 2, 69
effect of irradiation on, 2, 67 68
effect of oestrogens on 2, 60-65
inhibition of in guinea pigs, 2, 78
redundant, history and fate of 2, 59-68
ruptured, in guinea pigs, 2, 75-78
- Food, consumption of in 6 h, 5, 186
- Fowls, fertility of 3 20 21
- Freezing, resistance of tissue to 1 163 165
- Fructose, in placenta, 2, 120-122
production in placenta 2, 120, 121
- Fruit, ageing of, 2, 206
- Function, studies in human, 3 73-91
- Functional residual capacity variations with age, 3 60
- Gadiformes, growth of 5 160-166
lifespan of 5 148 160-166 223
metabolism of 5 169
size of 5, 148
- Galago, oogenesis in 2, 56
- Gall, arteriosclerosis in 5 109
- Galliformes, mortality rate of 5 101
- Gambusia affinis reproduction and senescence in, 5, 187 189
- Gannets, arteriosclerosis in, 5, 109
- Glar lifespan of 5, 222
- Gasterosteiformes, lifespan of 5 152, 223
- Gasterosteus aculeatus 3, 6
effect of on omen of 5, 168
- Geese, arteriosclerosis in, 5, 109
- Genes, relation with macromolecules, 3 47
- Genetical aspects of ageing, 1 238-41
3, 131 132-133 144 5 137
in *Drosophila* 5 278-280 283
- Germinal epithelium, proliferative powers of 1, 36, 37 38
- Gibberellin equilibrium, 4, 15-18 27 3, 30
- Gigantism of foetus, 2, 112, 162, 164, 166 167 171
- Gingival epithelium, effect of brushing on, 3 55-57 71 72
- Glomerular filtration rate, changes with age, 4, 231 238 246
effects of pyrogen 4, 237
in congestive heart failure, 4 275 277
- Glomerulonephritis, in man 5 77
in rats, 5 74-76
- Glucose, administration of in elderly schizophrenics 1 240-236, 237
diffusion of through aortic tissue 1 72 74
diffusion through tentorium cerebelli 1 74-75
in foetal liver 2, 136 145
in placenta, 2, 135-137 144 145
production in placenta, 2, 1 0 121
- Glutamic acid in elastin, 1 91 94 95 96
in plants, 2, 212
- Glutamine in senescent leaves, 2, 203 212
- Glycerophosphatase, in placenta, 2, 107 108
- Glycine in elastin, 1 91 94 95 96
- Glycogen, in apocrine sweat glands 2, 195
in placenta 2, 27-28 107 108 122, 123 135-137 144 145 159
- Glycogen storage effect of ACTH on 2, 24-25 29
effect of hormones on 2, 24
in bees 5 237 238 239
in liver age effects of 2 23-25 27 29
- Glycolysis, in dog aorta, 1 76
- Goats, lifespan of 3, 13 14 36
in placenta of 2, 120, 127 154-158, 159
placental development of 2, 155-158 159
radio-potassium uptake during pregnancy 2, 148-160
- Golden shiner lifespan of 5 223
- Goldfish, lifespan of 3 9 5 223
metabolism of 5 170
- Golgi complex 2, 68 89
- Gompertz Law 5 2, 72, 302
- Gompertz-Makeham equations, 5 117
- Gonadotrophic hormone, effect on foetus, 2, 28
effect on reproductive act, 2, 15
produced by pituitary gland 2, 21 22, 28
- Gonadotrophin, effect on ovary 1 150 151 152, 153 2, 31 35 55
effect on estrilized ovary 2, 49 51 57
ovulation induced by 2, 75 79 82
- Grass, protein in, 2, 03
respiration in 2, 206
- Graying, effect of environment of 5, 168
metabolism and lifespan in, 3, 26
- Grouper lifespan of 5 220
- Growth, 2, 251 5 296 298
body water changes due to 4, 103-106
effect of nutrition on, 1 126, 188

Growth

- effect of diet, 4, 116-138, 5, 84-85, 177, 378, 254-255
 effect on electrolytes, 4, 160
 effect on lifespan, 1, 29, 5, 147-159, 160-166
 in mice, 4, 136
 in rats, 4, 136
 relationship with lifespan, 5, 160-166
 utilization of protein in, 5, 182-186
- Growth hormone, action of, 1, 29, 2, 161-167, 171, 173-175
 effect on lifespan, 1, 29
- Growth rate, 1, 6
- Gurion, lifespan and size of, 5, 154
- Guinea pig, corpus luteum of, 2, 69-85
 fertility of, 3, 20
 follicular atresia in, 2, 59-60
 lifetime energy expenditure of, 5, 127
 oocytes in, 2, 36, 39, 41, 42, 54-55
 placenta of, 2, 110
 uterus of, 1, 167
- Gums, brushing of, 3, 51, 55-57, 71-72
 keratinization in, 3, 72
- Guppies, effect of diet on, 5, 169
 fecundity of, 5, 209
 growth of, 5, 229-230
 lifespan of, 3, 15-16, 30-31
 regeneration in, 5, 208-210
 reproduction in, 5, 171
- Gynaecomastia, in malnutrition, 3, 109, 109
- Habrobracon juglandis*, 5, 255
- Haddock, effect of age on fecundity, 5, 198-200
 fertility of, 3, 22
 lifespan and size of, 5, 148
 relationship of fecundity and body weight, 5, 200
 sex organs in, 5, 190
- Haemoglobin, changes in due to age, 4, 203, 206, 207
 in sheep, 4, 202, 203
 loss of from red cells, 2, 218, 219, 220
- Hair, effect of cortisone on, 2, 175
- Hake, lifespan and size of, 5, 148
- Halibut, lifespan and size of, 5, 148, 150
- Hamsters, hypothermia in, 1, 168, 2, 248
 in research on ageing, 1, 177, 181
 lifespan of, 1, 177
- Health, effect on sampling, 3, 183, 184
- Hearing, as measurement of ageing, 1, 6
- Heart, effect of potassium on, 4, 95-96
 output of, 3, 191
 changes with age, 3, 84-87
 stroke index of, 3, 87, 88
- Heart disease, in Africans, 3, 104, 111, 112, 113
 in man and rat, 5, 74-77
- Heart failure, congestive (see Congestive heart failure)
 in Africans, 3, 111

- Heat regulation, decline with age, 3, 63-64
- Hereditary haemorrhagic telangiectasia, 1, 85, 105
- Heredity, effect on lifespan, 1, 235-241
 rôle of in ageing, 1, 26, 27, 48
- Heron, lifespan of, 5, 99
- Herring, fecundity of, 5, 196-197
 growth of, 5, 146, 157, 158, 160-166
 lifespan, 5, 148, 156, 157, 158, 160-166
 relation of gonad growth to body weight, 5, 193
 relation of size and maturity, 5, 172
 size of, 5, 148
 survival curves of, 5, 143, 145
- Hesperoleucus venustus*, effect of environment on, 5, 168
- Heterandria formosa*, reproduction and age in, 5, 189
- Hibernation, effect on lifespan, 2, 249, 5, 103, 104
- Highland cattle, lifespan of, 5, 59, 61, 62
- Hippocampus hubonius*, lifespan of, 5, 147
- Hypoglossoides platessoides*, fecundity in, 5, 192
- Hypoclassus* spp., lifespan of, 5, 147
- Histidine, in elastin, 1, 96
- Holocentrus bermudensis*, protein metabolism in, 5, 183-185
- Homeostasis, disturbances of in infants, 4, 154-157
 effect of hormones on, 4, 165-179
 of water and electrolytes, effect of age, 4, 139-153
- Hormonal environment, effect on ovary, 1, 142, 146
- Hormones, effect on development of reproductive tract, 2, 3-18
 effect on electrolytes, 4, 313, 314
 effect on glycogen storage, 2, 24
 effect on homeostasis, 4, 165-179
 ovarian, 2, 48-52
 sensitivity of ovary to age changes in, 1, 142, 146
- Horses, breeding of, 5, 55
 causes of death in, 5, 68
 coat colour and longevity, 5, 49-50
 death curves of, 5, 56
 lifespan of under various climatic conditions, 5, 65-69
 lifespan of English thoroughbred, 5, 35, 56
 lifetime energy expenditure of, 5, 127
 survival curves of, 5, 37-42
- Houssely, ageing in, 5, 247-262
 effect of diet on, 5, 249, 253
 lifespan of, 5, 249-262, 287, 288
 effect of paternal age, 5, 259, 262
 sex differences in, 5, 255, 257
 sex ratio in, 5, 249
- Humming-birds, 3, 28
 lifespan of, 5, 103
- Hyalinization, in placenta, 2, 110
- Hydrogen ion gradient, 4, 34

- 17 Hydroxytestosterone, effect on water and electrolytes, 4, 79
 17 Hydroxyprogesterone, 1, 127 128
 Hydroxyprogesterone, in skin elastic tissue, 1, 68
 Hypercapnia, renal effects of 4, 265-266
 Hypercholesterolemia, 3, 136
 Hypernatraemia, and cerebral disturbances, 4, 36-44
 due to diarrhoea, 4, 36
 due to water deficiency 4, 38-44
 Hypertension, renal aspects of 4 258
 Hypotonic saline, effect on hyponatraemia, 4, 50
 Hyponatraemia, 4, 44-55, 95
 and cerebral disturbances, 4, 36-37
 and steroid output 4 60
 Hypophysectomy effect on foetus, 2, 166
 effect on ovary 2, 60-63
 Hypothalamus, effect on thirst, 4, 37
 Hypothermia, in hamsters, 1 168 1, 248
 Hypoxia, effect on d. penis, 4, 8

 Ide lifespan of 5, 223
 Inbred strains, 3, 6-8
 and parabiosis, 3 116, 124 127 129 130
 carcinoma in, 3, 117 118-119 120, 121
 cause of death in, 3, 120 121
 development of 3, 115-119 127
 in experimental gerontology 3, 115-130
 lifespan of 3, 11, 119-120, 121
 ovarian function in, 3, 119-120, 126 127
 survival of 3 13
 transplantation in, 3, 116, 120 122 123 1, 6, 129
 Index of cephalization, 5, 123, 135
 Individual performance, studies in, 3, 153 153, 164-167
 Infants, electrolyte metabolism in 4, 78-79 154-164
 water metabolism in 4, 78-79 154-164
 water retention in 4, 96-98
 Infection, resistance to as measure of aging, 1 6
 Infectious disease, in fish, 5, 213-214
 Insects (see also under names of species)
 aging in 5 247 268
 in nutritional research, 1 174 175
 lifespan of 5, 105
 overwintering in, 5 232 234 240
 immigration, artificial, 1 171
 larvae, effect on placenta, 2, 141
 larval sensitivity 1 237
 intellectual behaviour 3 175-177 182
 intelligence changes in with age 1 36-39 3, 170-187
 interstitial cells, in testis, 2, 91 96
 involuntary melanoblasts, 1, 44-45
 involuntary psychosis, 3, 134
 iodide diffusion of through aortic tissue, 3, 72 74

 Iron, content of apocrine sweat glands, 2, 191 193 195
 in heart muscle, 3 111 112
 metabolism of 3 109-110 112
 Irradiation, effect on lifespan, 5, 19 20, 138-141 282, 290 292
 effect on onset of disease, 5, 87, 88
 effect on ovary 3, 127
 effect on thyroid 3 55
 Isoleucine, in elastin 1, 91, 94 96

 Jack, lifespan of 5 220
 Jacob-Creutzfeldt's disease, 3, 234

 Kwashiorkor 1 190-191
 Karyoplasm, 2, 90 91
 Keratinization, in gums 3 72
 Ketosteroids, in testis, 2, 98, 99
 in urine, relationship with adrenal steroids, 1 128-130 133-139
 17 Ketosteroids, changes in excretion due to age, 4, 91
 daily excretion of 1, 131-133
 excretion of age changes in 2, 126-140
 in elderly and schizophrenics, 1, 221-222, 223-236
 in elderly subjects treated with steroids, 1 134-136
 Kidney, age changes in 4, 234-235
 amyloidosis in, 3 122, 125 126
 blood content of 3, 52 58
 blood flow in, 3, 191 192 4, 248
 age changes in, 3, 88
 changes in due to age, 4 227-228, 229-249 253-254
 concentrating ability of changes in due to age, 4 11 12, 243-244
 d. season of effects of age 4 250-263
 effect of D. benamine, 4 281, 282
 effect of obesity 4, 254 255 260
 effects of potassium deficiency on, 4, 262 263
 effects of pyrogen 4, 235-238
 effect of water deficiency of 4, 43
 enzymes in, 4 245
 function 4, 229
 in respiratory failure, 4 264-270
 variations with age, 1, 220
 glomerular filtration rate, changes due to age, 4 231 248
 in congestive heart failure, 4, 275 277
 growth of 4 251 252
 hormonal damage to 4, 256-258, 262
 in congestive heart failure, 4, 271, 273 276 282, 283 284 287
 in cor pulmonale, 4, 266-267
 lemons of causing loss of water 4, 39
 overloading producing senile changes, 4, 254-255, 260
 plasma flow in changes in due to age, 4, 229-231 235
 effect of pyrogen, 4, 237 238
 regeneration of 4, 251 253

- Growth**
 effect of diet, 4, 116-138, 5, 84-85, 177, 178, 254-255
 effect on electrolytes, 4, 160
 effect on lifespan, 1, 29, 5, 147-159, 160-166
 in mice, 4, 136
 in rats, 4, 136
 relationship with lifespan, 5, 160-166
 utilization of protein in, 5, 182-186
- Growth hormone**, action of, 1, 29, 2, 161-167, 171, 173-175
 effect on lifespan, 1, 29
- Growth rate**, 1, 6
- Grunion**, lifespan and size of, 5, 154
- Guinea pig**, corpus luteum of, 2, 69-85
 fertility of, 3, 20
 follicular atresia in, 2, 59-60
 lifetime energy expenditure of, 5, 127
 oocytes in, 2, 36, 39, 41, 42, 54-55
 placenta of, 2, 110
 uterus of, 1, 167
- Gums**, brushing of, 3, 51, 55-57, 71-72
 keratinization in, 3, 72
- Guppies**, effect of diet on, 5, 169
 fecundity of, 5, 209
 growth of, 5, 229-230
 lifespan of, 3, 15, 16, 30-31
 regeneration in, 5, 208-210
 reproduction in, 5, 171
- Gynecomastia**, in malnutrition, 3, 108-109
- Haemobrycon juglandis*, 5, 255
- Haddock**, effect of age on fecundity, 5, 198-200
 fertility of, 3, 22
 lifespan and size of, 5, 148
 relationship of fecundity and body weight, 5, 200
 sex organs in, 5, 190
- Haemoglobin**, changes in due to age, 4, 203-206, 207
 foetal, 4, 203-206, 207
 in sheep, 4, 202-203
 loss of from red cells, 2, 218-219, 220
- Hair**, effect of cortisone on, 2, 175
- Hake**, lifespan and size of, 5, 148
- Halibut**, lifespan and size of, 5, 148-150
- Hamsters**, hypothermia in, 1, 168, 2, 248
 in research on ageing, 1, 177-181
 lifespan of, 1, 177
- Health**, effect on sampling, 3, 183-184
- Hearing**, as measurement of ageing, 1, 6
- Heart**, effect of potassium on, 4, 95-96
 output of, 3, 191
 changes with age, 3, 84-87
 stroke index of, 3, 87-88
- Heart disease**, in Africans, 3, 104-111, 112-113
 in man and rat, 5, 74-77
- Heart failure**, congestive (see Congestive heart failure)
 in Africans, 3, 111
- Heat regulation**, decline with age, 3, 63-64
- Hereditary haemorrhagic telangiectasia**, 1, 85, 105
- Heredity**, effect on lifespan, 1, 238-241
 role of in ageing, 1, 26, 27, 48
- Heron**, lifespan of, 5, 99
- Herring**, fecundity of, 5, 196-197
 growth of, 5, 156, 157, 158, 160-166
 lifespan, 5, 148, 156, 157, 158, 160-166
 relation of gonad growth to body weight, 5, 193
 relation of size and maturity, 5, 172
 size of, 5, 248
 survival curves of, 5, 143, 145
- Hesperoleucus venustus*, effect of environment on, 5, 168
- Heterandria formosa*, reproduction and age in, 5, 189
- Hibernation**, effect on lifespan, 2, 249, 5, 103-104
- Highland cattle**, lifespan of, 5, 59, 61, 62
- Hippocampus hudsonius*, lifespan of, 5, 147
- Hippoglossoides platessoides*, fecundity in, 5, 192
- Hippoglossus* spp., lifespan of, 5, 147
- Histidine**, in elastin, 1, 96
- Holocanthus bermudensis*, protein metabolism in, 5, 183-185
- Homeostasis**, disturbances of in infants, 4, 154-157
 effect of hormones on, 4, 163-179
 of water and electrolytes, effect of age, 4, 139-153
- Hormonal environment**, effect on ovary, 1, 142-146
- Hormones**, effect on development of reproductive tract, 2, 3-18
 effect on electrolytes, 4, 313-314
 effect on glycogen storage, 2, 24
 effect on homeostasis, 4, 165-179
 ovarian, 2, 48-52
 sensitivity of ovary to age changes in, 1, 142-146
- Horses**, breeding of, 5, 55
 causes of death in, 5, 68
 coat colour and longevity, 5, 49-50
 death curves of, 5, 56
 lifespan of under various climatic conditions, 5, 65-69
 lifespan of English thoroughbred, 5, 35-56
 lifetime energy expenditure of, 5, 127
 survival curves of, 5, 37-42
- Humanly**, ageing in, 5, 247-262
 effect of diet on, 5, 249-255
 lifespan of, 5, 249-262, 287-288
 effect of paternal age, 5, 259-262
 sex differences in, 5, 255-259
 sex ratio in, 5, 249
- Humming-birds**, 3, 28
 lifespan of, 5, 105
- Hyallization**, in placenta, 2, 110
- Hydrogen ion gradients**, 4, 34

17 Hydroxycorticosteroids, effect on water and electrolytes, 4, 79
 17 Hydroxypregesterone, 1 127 128
 Hydroxyproline, in skin elastic tissue, 1 88
 Hypertension, renal effects of, 4, 265-266
 Hypercholesterolemia, 3, 136
 Hypernatremia, and cerebral disturbances, 4, 36-44
 due to diarrhea, 4 58
 due to water deficiency 4, 38-44
 Hypertension, renal aspects of 4, 258
 Hypertonic saline, effect on hyponatremia, 4, 50
 Hypohydratemia, 4, 44-55 95
 and cerebral disturbances, 4, 36-37
 and steroid output, 4, 60
 Hypophysectomy effect on foetus, 2, 166
 effect on ovary 2, 60-65
 Hypothalamus, effect on thirst, 4, 37
 Hypothermia, in hamsters, 1 168 2, 248
 Hypoxia, effect on diuresis, 4, 8

 Ide, lifespan of 5 223
 Infectious, 3, 6-8
 and parabiosis, 3, 116, 124 127 129 136
 carcinoma in, 3, 117 118-119 120 121
 cause of death in, 3 1 0 121
 development of 3 115-119 127
 in experimental gerontology 3 115-130
 lifespan of 3, 13 119-120, 121
 organ function in, 3, 119-1 0 126, 127
 survival of 3, 13
 transplantation in, 3 116 120 122 123 126, 129
 Index of cephalization, 5 123 135
 Industrial performance, studies in, 3 151 153 164-167
 Infants, electrolyte metabolism in 4, 78-79 154-164
 water metabolism in 4 78-79 154-164
 water retention in 4, 96-98
 Infection, resistance to, as measure of aging, 1 6
 Infectious disease, in fish, 5, 213-214
 Insects (see also under names of species)
 aging in 5, 247 268
 in nutritional research, 1 174, 175
 lifespan of 5, 105
 overwintering in, 5, 232-234 240
 immersion, artificial, 1 171
 insulin, effect on placenta, 3, 141
 insulin sensitivity 1 237
 intellectual behavior 3, 175-177 182
 intelligence, changes in with age, 1 36-39 3 170-187
 interstitial cells, in testis, 2, 91 96
 involuntary melancholia 1 44-45
 involuntary psychosis, 3 134
 iodide, diffusion of through aortic tissue, 1 72 74

Iron, content of apocrine sweat glands, 2, 191 193 195
 in heart muscle, 3, 111 112
 metabolism of 3 109-110 112
 Irradiation, effect on lifespan, 5, 19-20 138-141 282, 290 292
 effect on onset of disease, 5, 87 88
 effect on ovary 3, 127
 effect on thyroid 3 35
 Isoleucine, in plasma 1 91 94, 96

 Jack, lifespan of 5 220
 Jacob-Creutzfeldt disease, 3 134

 Kwashiorkor 1 190-191
 Karyoplasm, 2, 90 91
 Ketatinization, in gums, 3, 72
 Ketosteroids, in testis, 2, 98 99
 in urine, relationship with adrenal steroids, 1 1 8-130 133-139
 17 Ketosteroids, changes in excretion due to age, 4, 91
 daily excretion of 1 131 133
 excretion of age changes in, 1, 126-140
 in elderly and schizophrenics, 1 221-222, 223-236
 in elderly subjects treated with steroids, 1 134-136
 Kidney age changes in, 4, 234-235
 amyloidosis in 3, 12, 125 1-6
 blood content of 3 52 58
 blood flow in, 3 191 192 4, 248
 age changes in, 3 88
 changes in due to age, 4, 227 228, 229-249 253-254
 concentrating ability of changes in due to age, 4 11 12, 243-244
 deases of effects of age 4 250-263
 effect of D benamine, 4, 281 282
 effect of obesity 4, 254 255 260
 effects of potassium deficiency on 4, 262 263
 effects of pyrogen 4 235-238
 effect of water deficiency of 4, 43
 enzymes in, 4 245
 function 4 229
 in respiratory failure, 4 264-270
 variations with age 1, 220
 glomerular filtration rate, changes due to age, 4 231 248
 in congestive heart failure, 4, 275 277
 growth of 4 251 252
 hormonal damage to 4, 256-258, 262
 in congestive heart failure, 4 272, 273 276 282, 283 284 287
 in cor pulmonale, 4 266-267
 lesions of causing loss of water 4, 39
 overloading producing senile changes, 4, 254-255 260
 plasma flow in changes in due to age, 4 229-231 235
 effect of pyrogen 4 237 238
 regeneration of 4, 252 253

Growth

- effect of diet 4, 116-138, 5, 84-85, 177, 178, 254-255
- effect on electrolytes, 4, 160
- effect on lifespan, 1, 29, 5, 147-159, 160-166
- in mice, 4, 136
- in rats 4, 136
- relationship with lifespan, 5, 160-166
- utilization of protein in 5, 182-186
- Growth hormone, action of, 1, 29, 2, 161-167 171, 173-175
- effect on lifespan, 1, 29
- Growth rate, 1, 6
- Grunion, lifespan and size of, 5, 154
- Guinea pig, corpus luteum of, 2, 69-85
- fertility of 3, 20
- follicular atresia in, 2, 59 60
- lifetime energy expenditure of 5, 127
- oocytes in, 2, 36 39, 41, 42, 54-55
- placenta of, 2, 110
- uterus of 1, 167
- Gums, brushing of 3, 51, 55-57, 71-72
- keratinization in 3, 72
- Guppies, effect of diet on 5, 169
- fecundity of, 5, 209
- growth of 5, 229 230
- lifespan of 3, 15-16 30-31
- regeneration in 5, 208-210
- reproduction in 5, 171
- Gynecomastia, in malnutrition 3, 108-109
- Habrobracon juglandis* 5, 255
- Haddock, effect of age on fecundity 5, 198-200
- fertility of, 3, 22
- lifespan and size of 5, 148
- relationship of fecundity and body weight 5, 200
- sex organs in 5, 190
- Haemoglobin, changes in due to age 4, 203, 206 207
- foetal, 4, 203 206 207
- in sheep 4, 202 203
- loss of from red cells, 2, 218 219, 220
- Hair, effect of cortisone on 2, 175
- Hake, lifespan and size of 5, 148
- Hallibut, lifespan and size of 5, 148 150
- Hamsters, hypothermia in, 1, 168 2, 248
- in research on ageing, 1, 177 181
- lifespan of 1, 177
- Health, effect on sampling, 3, 183 184
- Hearing, as measurement of ageing, 1, 6
- Heart, effect of potassium on, 4, 95-96
- output of 3, 191
- changes with age, 3, 84-87
- stroke index of 3, 87 88
- Heart disease, in Africans, 3, 104 111 112, 113
- in man and rat, 5, 74-77
- Heart failure, congestive (see Congestive heart failure)
- in Africans, 3, 111

- Heat regulation, decline with age, 3, 63-64
- Hereditary haemorrhagic telangiectasis, 1, 85, 105
- Heredity, effect on lifespan 1, 238-241
- role of in ageing, 1, 26, 27, 48
- Herons, lifespan of, 5, 99
- Herring, fecundity of, 5, 196-197
- growth of, 5, 156, 157, 158, 160-166
- lifespan, 5, 148, 156, 157, 158, 160-166
- relation of gonad growth to body weight, 5, 193
- relation of size and maturity, 5, 172
- size of, 5, 148
- survival curves of, 5, 143, 145
- Hesperoleucus venustus*, effect of environment on 5, 168
- Heterandria formosa*, reproduction and age in 5, 189
- Hibernation, effect on lifespan, 2, 249 5, 103-104
- Highland cattle, lifespan of 5, 59, 61, 62
- Hippocampus hudsonius*, lifespan of 5, 147
- Hippoglossoides platessoides* fecundity in, 5, 192
- Hippoglossus* spp. lifespan of 5, 147
- Histidine, in elastin, 1, 96
- Holocanthus bermudensis*, protein metabolism in, 5, 183-185
- Homeostasis, disturbances of in infants, 4, 154-157
- effect of hormones on 4, 165-179
- of water and electrolytes, effect of age 4, 139-153
- Hormonal environment, effect on ovary 1, 142 146
- Hormones, effect on development of reproductive tract, 2, 3-18
- effect on electrolytes, 4, 313 314
- effect on glycogen storage 2, 24
- effect on homeostasis, 4, 165-179
- ovarian 2, 48-52
- sensitivity of ovary to age changes in, 1, 142-146
- Horses, breeding of 5, 55
- causes of death in 5, 68
- coat colour and longevity 5, 49-50
- death curves of 5, 56
- lifespan of under various climatic conditions, 5, 65-69
- lifespan of English thoroughbred, 5, 35 56
- lifetime energy expenditure of 5, 127
- survival curves of 5, 37-42
- Housety, ageing in, 5, 247 262
- effect of diet on 5, 249-255
- lifespan of 5, 249-262 287 288
- effect of paternal age 5, 259 262
- sex differences in, 5, 255 259
- sex ratio in 5, 249
- Humming-birds, 3, 28
- lifespan of 5, 105
- Hyalinization, in placenta 2, 110
- Hydrogen ion gradients, 4, 34

- 17 Hydroxycorticosteroids, effect on water and electrolytes, 4, 79
 17 Hydroxyprogesterone, 1 127 128
 Hydroxyproline, in skin elastic tissue, 1 33
 Hypercapnia, renal effects of 4, 265-266
 Hypercholesterolaemia, 3, 136
 Hypernatraemia, and cerebral disturbances, 4, 36-44
 due to diarrhoea, 4, 58
 due to water deficiency 4, 38-44
 Hypertension, renal aspects of 4, 258
 Hypertonic saline, effect on hyponatraemia, 4, 40
 Hyponatraemia 4, 44-55, 95
 and cerebral disturbances, 4 36-37
 and steroid on put, 4, 60
 Hypophysectomy effect on foetus, 2, 166
 effect on dry 2, 60-65
 Hypothalamus, effect on thirst, 4, 37
 Hypothermia, in hams etc, 1 168 2, 268
 Hypoxia, effect on diuresis, 4, 8
- Ide, lifespan of 5, 223
 Inbred strains, 3 6-8
 and parabiosis, 3, 116 124 127 129 130
 carcinoma in, 3 117 118-119 120 125
 cause of death in, 3 120 121
 development of 3 115-119 127
 in experimental gerontology 3, 115-130
 lifespan of 3 13 119-120, 121
 ovarian function in, 3, 119-120 126, 127
 survival of 3, 13
 transplantation in, 3, 116 120 122 123 126 129
 Index of cephalization, 5 123 135
 Industrial performance, studies in, 3 151 153 164-167
 Infants, electrolyte metabolism in 4, 78-79 154-164
 water metabolism in 4 78-79 154-164
 water retention in, 4, 96-98
 Infertility, resistance to as measure of ageing, 1 6
 Infectious disease, in fish, 5, 213-214
 Insects (see also under names of species)
 ageing in 5 247 268
 nutritional research 3 174 175
 lifespan of 5, 105
 overwintering in, 5, 232-234 240
 Insensitization, artificial, 1 171
 Insulin, effect on placenta, 2, 141
 Insulin sensitivity 1 237
 Intellectual behaviour 3 175-177 182
 Intelligence, changes in with age, 1 36-39 3, 170-187
 Interstitial cells, in testis, 2, 91 96
 Isolational melancholia, 1 44-45
 Irradiational psychosis, 3, 134
 Iodide diffusion through aortic tissue, 1 72 74
- Iron, content of apocrine sweat glands, 2, 191 193 195
 in heart muscle, 3 111 112
 metabolism of 3, 109-110 112
 Irradiation, effect on lifespan, 5, 19-20 138-141 282, 290, 292
 effect on onset of disease, 3, 87 88
 effect on ovary 3 127
 effect on thyroid 3 53
 Isoleucine, in class n, 1 91 94, 96
- Jack, lifespan of 5, 20
 Jacob-Creutzfeldt's disease 3 134
- Kwashiorkor 1 190-191
 Karyoplasm, 2, 90, 91
 Keratinization, in gums, 3, 72
 Ketosteroids, in testis, 2, 98 99
 in urine, relationship with adrenal steroids, 1 128-130 133-139
 17 Ketosteroids, changes in excretion due to age, 4, 91
 daily excretion of 1 131 133
 excretion of age changes in, 1 126-140
 in elderly and schizophrenics, 1 221 222, 223-236
 in elderly subjects treated with steroids, 1 134-136
- Kidney, age changes in 4, 234-235
 amplio dosis in, 3 122, 125 126
 blood content of 3, 52, 58
 blood flow in, 3 191 192 4, 248
 age changes in, 3 88
 changes in due to age, 4, 227 228, 229-249 253-254
 concentrating ability of changes in due to age, 4, 11 12, 243-244
 diseases of effects of age 4 250-263
 effect of D-benamine 4 281 282
 effect of obesity 4 254 255 260
 effects of potassium deficiency on, 4, 262 263
 effects of pyrogen, 4, 235-238
 effect of water deficiency of 4 43
 enzymes in, 4, 245
 function 4 229
 in respiratory failure, 4, 264-270
 variations with age 1 220
 glomerular filtration rate, changes due to age, 4, 231 248
 in congestive heart failure, 4, 275 277
 growth of 4 251 252
 hormonal damage to 4, 256-258, 262
 in congestive heart failure, 4, 272, 273 276 282, 283 284, 287
 in cor pulmonale, 4 266-267
 lesions of cause of loss of water 4, 39
 overloading producing senile changes, 4 254-255 260
 plasma flow in changes in due to age, 4, 229-231 235
 effect of pyrogen 4, 237 238
 regeneration of 4, 252-253

Lifespan

- of cattle, 5, 57-65, 70-71
- of cavy 3 12, 13
- of cells, 2, 216, 227 3, 5
- of *Cervus elaphus* 5, 92 94
- of chaffinch 3 9
- of *Chiropodomys glurodes* 5 96
- of *C. ellus pygmaeus* 5 97
- of cockroaches 5, 253-254
- of deer 3, 12 5 91 94
- of dingoes, 3, 12
- of dogs, 3, 12, 13 14 17 5 134
- of *D. podomys hermanni* 5 96
- of *Dolicho is pa agona* 3 12, 13
- of *Drosophila subobscura* 5 262, 266
- of elephants, 1 244
- of English thoroughbred horses, 5, 35 56
- of finch 5 99 101
- of fish, 1 28 29 3 9 15-16
 - characteristics of long 5 217 218
 - in captivity 5 212 230
 - in Nature 5 14 180
 - of different species, 5 219-224
- of flies 5 105
- of goats, 3 13 14 36
- of goldfish 3 9 5 223
- of guinea pigs 3 15-16 30-31
- of Hasting mares, 5 43
- of hamsters, 1 177
- of beavers, 5 99
- of Hokkaido ponies, 5, 43
- of horses 5 35-56, 65-69
- of housefly 5 249-262, 287 288
 - sex differences in, 5, 255-259
- of human beings, actuarial aspects, 5 2-10
- of humming-birds, 5 103
- of mixed strains, 3 13 119-120 121
- of insects 5, 105
- of *Lagotis a senegalis* 5 99
- of *Lebistes reticulatus* 3 15-16 30-31
- of Lipisa horses 5 43
- of lizards, 3 26 27
- of lupus 3, 12
- of mammals, 3 9 14
- of mammals in Nature, 5 90-105
- of man and woman compared 5, 10-11 16
- of *Megadontomys* 5 100
- of mice 1 177 3 9 5 95-96 287
- of *Microtus* 3 10
- of monk seals, 5 105
- of *Mus mus mus* 3 12
- of *Mus* 3 9
- of *Myomyscus* 5 97
- of nightingale 3 12
- of *Odontomys hemionus* 5 92 94
- of owl 5 99
- of *Orizella* 5 92 94
- of *Orizomys* 3 13 14
- of *Paramyrus* 3 16
- of parent and progeny correlated 5 47-49

Lifespan

- of *Parus major* 5 100
- of *Passer domesticus* 5 99
- of Passerines, 5 99-100
- of *Perognathus* 3, 9 10
- of *Peromyscus* 3, 9 10
- of *Peromyscus leucopus* 5 95-96
- of rabbits, 1 181 3 11 5 97
- of *Rangifer arcticus* 5, 92 94
- of rats, 1 177 178 179 180 5 95-96 251 252
 - effect of diet, 5 78
 - effect of disease 5 72-89
- of red cells, 2, 217 233 234 238 239 241 245
- of sheep 3 12, 13 14 15 5, 91 94
- of shrews, 5 97
- of *Sorex araneus*, 5 97
- of soulik 5, 97
- of sparrows, 5 99
- of *Sterna hirundo* 5 97-99
- of *Strix aluco* 5, 99
- of swiftness, 5 100 103 104
- of terns, 5 97 99 104
- of ticks 5 100
- of *Takophya* 1, 187 191
- of trout, 1 29 5 222, 263
- of twins, 3 140 141
- of ungulates 5 91-95
- of vertebrates, 3 9 10 11 17
- of wolfhound 3 12, 13
- of wolves, 3 12, 14
- relationship to index of cephalization 5 123-125
- relationship with growth 5 160-166
- sex differences in 3, 30
- sexual maturity and 1 29 30
- Life-tables, 1 9-10 5 9-11
 - limits of 5 11 12, 18
- Light, effect on ageing of leaves, 2, 211
 - effect on deer antler growth 2, 181 182
- Liver carcinoma of 3, 106 107 113
 - focal, glucose production in 2, 136 145
 - relationship with placenta, 2, 108 109
 - glycogen storage in age effects of 2, 23-25 27 29
 - in fish 5, 227
 - mitochondria in 2, 101
- Liver disease, in Africans, 3, 107 111 188-190
 - in fish, 5 215-216
- Lizards, metabolism and lifespan in 3 76 27
 - parasites in 3, 33
- Longevity (see also Lifespan)
 - onset of disease and 5 74-89
- Longitudinal studies, 3 163 164 172, 173 174
- Look-down, lifespan of 5 221
- Lophus piscator in relation to 5 99
- Lowest sea level mortality rate of 5 146

- Lung, age changes in 1, 65
 blood flow in, 1, 67
 cancer of in old people 1, 21
 diseases of 3, 77-79
 in rats, 5, 82
 effects of age on, 4, 264
 elastic resistance of, 1, 58, 60, 61, 63, 65
 function of 3, 77-78
 mixing of air in 1, 68
 volume of variations with age, 1, 58, 60 65 66, 67 68
- Lungfish, lifespan of 5 224
- Lupus, lifespan of 3, 12
- Lymantria dispar* 3, 24
- Lymphocytes, levels of variations with age 1, 224 231 232
- Lysine, in elastin 1, 96
 in plants 2, 212
- Mackerel, lifespan and size of 5, 154
- Magnesium deficiency of 4, 301-310
 signs of 4 304 307 309-310
 in bone, 4, 309
 in plasma 4, 99-100
 in rat body 4, 120 121
- Makeham's Law, 5 2 302
- Malayan flying barb, lifespan of 5, 224
- Mallothus villosus* mortality rate of 5, 146
- Malnutrition, effect of 1 205
 effect on body fluids 4, 156-157
 in Africans 3, 188-190
 water metabolism in 4, 156-157
- Mammals, arteriosclerosis in 5, 109
 lifespan of 3, 9 10
 in Nature 5 90-105
 life-tables of 5, 117 118
 relationship of brain and body weight to lifespan 5 115 139
- Man, disease in effect on lifespan 5, 72 89
 lifetime energy expenditure of 5, 127
- Mandibular glands in bees 5, 233
- Manual work, performed by elderly people 1, 216
- Maternal age, effect on lifespan 5 23-27 31, 32
- Maturation, definition of 1 202
 delay of and lifespan 1, 27-30
 effect of nutrition on 1, 189-190
 effect on lifespan 1, 27-30 201-208
 rapid, as cause of ageing 1, 194-199
- Mealworm, effect of paternal age on lifespan 5, 262
- Megadyptes antipodes* lifespan of 5, 100
- Melanogrammus aeglefinus*, fecundity of 5, 198-200
 sex organs in 5, 190
- Membranes, diffusion coefficients for solutes for, 1, 69-79
 permeability of effect of enzyme inhibitors, 1, 78
- Memory, 3, 187
 age changes in, 3, 65
 in centenarians 1, 25
- Memory
 in old people 1, 40-41
 in rats, 1, 215
- Menarche, age of 1, 202
- Menopause, ovarian changes in, 1, 144-146
- Menstrual cycle, acid base balance in, 4, 93
 effect on water and electrolytes, 4, 81-88
 sodium/potassium ratios during, 4, 83-88
- Menstruation, effect on apocrine sweat glands 2, 196-198, 199-200
 restoration of after cessation, 1, 144-145
- Mental ability, adaptation in 3, 62
 decline of with age 3, 64-65
- Mental aspects of ageing, 1, 32-52
- Mental disease, genetics of 3, 133-134, 137, 144
 in Africans 3, 145
 in old people 1, 45-46
- Mental excitement, due to magnesium deficiency 4, 304 307 309-310
- Mental testing, 3, 176 181, 182 183-184, 186
- Mercury poisoning excretion of sweat in, 4, 99
- Meriones libycus* 3, 51 57
- Metabolic disease, in fish, 5, 216
- Metabolic disturbances in infants 4, 154-164
- Metabolism, comparison between infant and adult 4 157-159
 effect of undernutrition 1, 189
 effect on lifespan 5, 103 104 124-126 129 136-137 169 170
 in senescent leaves 2, 202 214
- Metabolic rate, effect on lifespan 3, 31
 relationship with ageing 3, 23-28
- Methionine, in elastin 1, 96
- Mice, amyloidosis in 5, 80-81
 effect of diet on 5, 79-80
 effect of X irradiation on ovary of, 2, 49-50 57
 growth in 1, 204
 lifespan of 1, 177 3, 9 5, 95-96, 287
 ovarian changes in 1, 146
 white footed lifespan of, 5, 95-96
- Microtus* lifespan of 3, 10
- Müller's thumb, lifespan of 5, 223
- Minerals, in pollen 5, 237
 intake of effect on body composition, 4, 116-138
- Minnow, lifespan and size of, 5, 152
- Mitochondria, appearance of 2, 100
 division of 2, 103 104
 in adrenal cortex 2, 101 102 103
 in adrenal glands 2, 101, 102
 in different physiological states 2, 100-104
 in Leydig cells 2, 93

- Mitochondria
in liver 2, 101
in pancreas, 2, 101
in placenta, 2, 107
in yolk sac, 2, 101
Mitosis, 2, 230, 231
in apocrine sweat glands, 2, 196, 199
Mitotic inhibitors, 5, 136
Moles macrocephala, 3, 24
Molecular changes in ageing, 5, 129-131
Molluscs, 3, 25
Monkeys, arteriosclerosis in, 5, 108
in research on ageing, 1, 182
menstrual cycle, 1, 145-146
oogenesis in, 2, 44, 55
ovulation in, 2, 67
Moonfish, lifespan of 5, 221
Mortality relation with age and growth,
5, 160-166
theory of 5, 127-129
Mortality rates, 5, 216-46
laws governing, 5, 2-5
mathematical models for 5, 302-311
sex differences in 5, 81
Mosquito, effect of diet on, 5, 255
lifespan of 5, 105
Mosquito fish, mortality rates of 5, 167
reproduction and senescence in, 5, 187-189
Mothers, age of effect on lifespan, 5, 23-27, 31-32
Motivation, 3, 154-156, 185, 186, 187
Mugiloides, lifespan and size of 5, 154
Müllerian ducts, normal development of 2, 3, 13-14
Muraena muraena, lifespan of 3, 12
Muraena, lifespan of 3, 9
Muraena muraena (see Housefly)
Muscle, and yolk of sodium deficiency 4, 49-50
composition of 4, 23
electrolytes in, 4, 21, 22, 164, 224-225
potassium in 4, 289-291
power of 1, 137
as measure of ageing, 1, 6
water in 4, 21, 22, 113, 163-164
Muscular degeneration, 5, 77
in rats, 5, 74-76
Muskhallung, lifespan of 5, 221
Mutation, 3, 43-44, 45
Mykaran, effect on oogenesis, 2, 43
Myocardial degeneration, 5, 77
in rats, 5, 74-76
Myon mystacinus, lifespan of 5, 97
Naevi, spider 1, 81-82
Nasturtium, pinnate, 2, 203
Natrix natrix, fertility of 3, 2, 22
Naturalists, longevity in 1, 52
Neohumanus macropus, fecundity of 5, 193
Nephrectomy effects of, 4, 252, 255, 257
Nephrosis, in man 5, 77
in rats, 5, 74-76, 83
Nerve cells, 2, 250, 251
in bees, 5, 234-244
pigment in, 3, 45
Nervous disease, incidence of in old people 1, 0
Nervous system, adaptation in 3, 61
Nolhuise, lifespan of 3, 12
Nitrogen, diffusion of through aortic tissue, 1, 72-74
excretion of changes due to age, 4, 243
in pollen 5, 236
in rat body 4, 120-121
Normal, definition of 3, 74, 94, 190-193
Nucleic acids, in cells, 3, 48-49
Nutrition, and ageing, 1, 186-193
and disease in Africans, 3, 104-114, 145, 188-190
effect on cell, 1, 191
effect on deer antlers, 2, 184
effect on growth, 1, 186, 188
effect on lifespan, 1, 186-193, 194-199, 3, 74, 25, 28, 34, 35, 36
effect on pregnant ewes, 2, 184
in Africans, 3, 188, 190
neglected research areas in 1, 173-185
Obesity effect on kidney 4, 254, 255
Odontococcus hemionus, lifespan of 5, 92-94
Oesophagus, cancer of in old people, 1, 21
Oestradiol, effects on development of reproductive tract, 2, 11-17
Oestrogen, effect on ovary 2, 60-65
effect on placenta, 2, 142
effect on water retention 4, 79, 84, 86
excretion of changes in due to age, 4, 91
secretion of 2, 49-50, 51, 52
Oestrus, in X irradiated mice, 2, 49-50
Onco hynchus nerka, fecundity in, 5, 197, 198
growth of 5, 156, 157, 158
Onco hynchus spp., mortality rates of 5, 145
Oocytes, atresia of 2, 44-45
decline of with age 2, 32
effect of X irradiation on, 2, 49, 50, 51
formation of in ovary 2, 32-48
number of 2, 43, 47, 54-55
Oogenesis, 1, 147, 149, 2, 32-48, 55-56
effect of Mykaran on 2, 43
effect on of hypophysectomy 2, 25, 41, 44
in armadillo 2, 39, 40
in Dorcus 2, 56
in dog, 2, 43
in galago 2, 36
in guinea pig, 2, 36, 39, 41, 42
in lemur 2, 39-40
in monkey 2, 44, 55
in rabbit, 2, 36-37
in rats, 2, 42-43
in seal, 2, 37
Ophiocephalus, lifespan of 5, 224
Orange chromate, lifespan of 5, 224

- Lung**, age changes in, 1, 65
 blood flow in, 1, 67
 cancer of in old people, 1, 21
 diseases of, 3, 77-79
 in rats, 5, 82
 effects of age on, 4, 264
 elastic resistance of, 1, 58, 60, 61, 63, 65
 function of, 3, 77, 78
 mixing of air in, 1, 68
 volume of, variations with age, 1, 58, 60, 65, 66, 67, 68
- Lungfish**, lifespan of, 5, 224
- Lupus**, lifespan of, 3, 12
- Lymantria dispar***, 3, 24
- Lymphocytes**, levels of, variations with age, 1, 224, 231, 232
- Lysine**, in elastin, 1, 96
 in plants, 2, 212
- Mackerel**, lifespan and size of, 5, 154
- Magnesium**, deficiency of, 4, 301-310
 signs of, 4, 304, 307, 309-310
 in bone, 4, 309
 in plasma, 4, 99-100
 170 171
- Malnutrition**, effect of, 1, 156-157
 effect on body fluids, 4, 156-157
 in Africans, 3, 188-190
 water metabolism in, 4, 156-157
- Mammals**, arteriosclerosis in, 5, 109
 lifespan of, 3, 9, 10
 in Nature, 5, 90-105
 life-tables of, 5, 117-118
 of brain and body weight
- Mandibular glands**, in bees, 1, 216
- Manual work**, performed by elderly people, 1, 216
- Maternal age**, effect on lifespan, 5, 23-27, 31, 32
- Maturation**, definition of, 1, 202
 delay of and lifespan, 1, 27-30
 effect of nutrition on, 1, 189-190
 effect on lifespan, 1, 27-30, 201-208
 rapid, as cause of ageing, 1, 194-199
- Mealworm**, effect of paternal age on lifespan, 5, 262
- Megadypus antipodes***, lifespan of, 5, 100
- Melanogramma oeglefinis***, fecundity of, 5, 198-200
 sex organs in, 5, 190
- Membranes**, diffusion coefficients for solutes for, 1, 69-79
 permeability of, effect of enzyme inhibitors, 1, 78
- Memory**, 3, 187
 age changes in, 3, 65
 in centenarians, 1, 25
- Memory**
 in old people, 1, 40-41
 in rats, 1, 215
- Menarche**, age of, 1, 202
- Menopause**, ovarian changes in, 1, 144-146
- Menstrual cycle**, acid-base balance in, 4, 93
 effect on water and electrolytes, 4, 81-88
 sodium/potassium ratios during, 4, 83-88
- Menstruation**, effects on apocrine sweat glands, 2, 196-198, 199-200
 restoration of after cessation, 1, 144-145
- Mental ability**, adaptation in, 3, 62
 decline of with age, 3, 64-65
- Mental aspects of ageing**, 1, 32-52
- Mental disease**, genetics of, 3, 133-134, 137, 144
 in Africans, 3, 145
 in old people, 1, 45-46
- Mental excitement**, due to magnesium deficiency, 4, 304, 307, 309-310
- Mental testing**, 3, 176, 181, 182, 183-184, 186
- Mercury poisoning**, excretion of sweat in, 4, 99
- Meriones libycus***, 3, 51, 57
- Metabolic disease**, in fish, 5, 216
- Metabolic disturbances**, in infants, 4, 154-164
- Metabolism**, comparison between infant and adult, 4, 157-159
 effect of undernutrition, 1, 189
 effect on lifespan, 5, 103-104, 124-126, 129, 136-137, 169-170
 in senescent leaves, 2, 202-214
- Metabolic rate**, effect on lifespan, 3, 31
 relationship with ageing, 3, 23-28
- Methionine**, in elastin, 1, 96
- Mice**, amyloidosis in, 5, 80-81
 effect of diet on, 5, 79-80
 effect of X-irradiation on ovary of, 2, 49-50, 57
 growth in, 1, 204
 lifespan of, 1, 177, 3, 9, 5, 95-96
- Mitochondria**, appearance of, 2, 103, 104
 division of, 2, 103, 104
 in adrenal cortex, 2, 101-102, 103
 in adrenal glands, 2, 101, 102
 in different physiological states, 2, 100-104
 in Leydig cells, 2, 93

- Phenylalanine, in elastin, 1, 96
 Phosphate, excreted on in elderly and schizophrenics, 1, 221-222, 223 236
 excretion in respiratory acidosis, 4, 266
 in babies urine, 4, 211, 213 215 216
 Phospholipin, in placenta, 2, 122
 Phosphorus, effect of protein intake, 4, 121, 127 128
 excess of 4, 144 143-146
 in body of rat, 4 120 121 127-128
 intake of 4, 142
 Phosphorylation, in plant cells 2, 208
 Physiological function, stability of 5 145
 Pick's disease, 3, 134 135-136 143-144, 146
 Pigmentation, rôle of in ageing processes, 1, 53 54
 Pigments in nerve cells, 3, 44
 Pigs, effect of nutrit on on growth 1, 188
 Pike, lifespan of 5, 222
 Pike-kulie, lifespan of 5 224
 Pilchards, 3 26
 Pilot fish, lifespan of 5 221
 Pitressin, effect on hyponatraemia, 4, 53-55
 effect on water diuresis, 4, 7-8, 11
 variation of effect due to age, 4 239-240
 Pituitary gland, control of by testis, 2, 20-21 28
 control of on embryo 2, 165 166, 174
 effect on electrolytes, 4, 166 167
 excision of effect on oogenesis, 1, 35 41 44
 function of age factor in, 2, 20-23
 gonadotrophic hormone produced by 2, 21-22, 28
 relationship with adrenal cortex, 2, 22
 relationship with thyroid, 2, 21
 thyrotrophic hormone produced by 2, 21-22
 transplantation of 1 152 153
 Pituitary hormones, effect on ovary 1, 142, 143 144-145
 Placenta acid phosphatase in 2, 107 108
 adenosine triphosphate in 2, 107, 108
 ageing in biochemical evidence 2, 129-147
 morphological aspects 2, 105-117
 biochemical changes in 2, 107 109
 blood flow in 2, 125 126
 calcium in 2, 110
 cholesterol in 2 122
 collagen in 2, 146
 cytological changes in 2 107
 effect of corpus luteum on 2, 84
 effect of cortisone on 2, 141
 effect of hormones on glucose metabolism, 2, 141 142, 146
 effect of insulin on 2, 141
 effect of oestrogens on, 2, 142
 enzymes in, 2, 107 108 141 145
 fibrin in 2, 110
 fibrinoid in, 2, 110
 fructose in 2, 120 121 122

Placenta

- function of chronological changes in, 2, 118-128
 glucose in, 2, 135-137, 144 145
 glucose production in, 2, 120, 121
 glycerophosphatase in 2, 107 108
 glycogen in 2, 27-28, 107, 108, 122, 123, 130, 133-134, 137, 159
 effect of progesterone, 2, 123, 126
 hyalinization in, 2, 110
 in postmaturity, 2, 112-113
 in toxæmia of pregnancy, 2, 112
 lactic acid in, 2, 137, 141
 length of gestation and 2, 110, 111
 lipids in 2, 122
 mitochondria in 2, 107
 of goat, 2, 154-158
 of guinea pig, 2, 110
 of rabbit, 2, 108
 of rat, 2, 110
 oxygen consumption in 2, 131-132
 permeability of 2, 118 119, 126
 permeability of barrier 2, 109, 116
 phospholipin in 2, 122
 pregnancy changes in, 2, 110-111, 115
 pyruvate in, 2, 137
 radio-potassium uptake of in pregnancy 2, 148-160
 relationship with foetal liver, 2, 108, 109
 sodium transfer in 2, 111
 structure of 2, 105-106, 116
 succinic dehydrogenase in, 2, 107, 108
 surface area of 2, 115
 vili of in goat 2, 155-158
 weight of, 2, 120 124, 125, 127, 146
 Placentome, in goat, uptake of radio-potassium in 2, 151-154 159
 Place, fecundity of 5 202-206
 growth of 5, 157 158 159
 lifespan and size of 5, 150
 mortality rates of 5, 167
 reproduction and growth in, 5, 189-190
 Plants, amino acids in 2, 212
 Plasma, concentrations of ions in, 4, 25-26
 magnesium in 4, 99-100
 potassium in 4 65
 sodium in, 4, 65
 urea in, 4, 67
 Plasma proteins, in liver disease 3, 112
Pleuronectes platessa fecundity in, 5, 202 206
 growth of 5, 157 158
 reproduction and growth in, 5, 189-190
Pleuronectoides, lifespan and growth of, 5, 161 166
 lifespan and size of 5 148
 Pneumonia, incidence of in old people, 1, 19
 Poeclidae, effects of age on reproduction of 5, 181 186-189
 Pollen, content of 5, 237
 effect on bees, 5, 236-240

- Organ culture studies of foetal reproductive tract, 2, 3-17
 Osler's disease, 1, 85 105
 Osmotic diuresis, 4, 40
 Osteoporosis, calcium metabolism in, 1, 109, 110 116-118 121 122, 123, 125
 senile incidence of, 1, 125
 Ova, age changes in, 3, 126-127, 149-150
 age of, 1, 172
 age of at time of ovulation, 1, 147-149
 ageing of, transplantation techniques in study of, 1, 150-159
 lifespan of, 1, 148 149
 transfer of, 1, 150
 Ovaries, age changes in, 3, 119, 126
 transplantation techniques in study of, 1, 150-159
 amyloidosis of, 3, 125
 androgen production in, 2, 15-16
 changes in, 1, 148
 changes in at end of reproductive life, 1, 144-146
 changes in at puberty, 1, 143-144
 changes in before puberty, 1, 142-143
 effect of age on in fish, 5, 201
 effect of gonadotrophin on, 1, 150 151, 153 2, 31 35 55
 effect of hypophysectomy on, 2, 60
 effect of irradiation on, 2, 34, 49-51, 3, 127
 effect of oestrogen on, 2, 60-65
 formation of oocytes in, 2, 32-48
 grafting of, 1, 150-152 154-157
 oocyte survival in, 2, 33
 growth of in herring, 5, 195
 hormonal secretions of, 2, 48-52
 hypertrophy of effect on oocytes, 2, 34-35
 in bees, 5, 233 235 237 238 239 243
 in *Drosophila*, 5, 275 277 285
 in fish, 5, 193
 changes due to age, 5, 182
 life of, 1, 142 147
 lifespan of cells of, 1, 142
 low temperature storage of, 1, 165
 regenerative capacity of, 2, 31-58
 sensitivity of to hormonal environment, 1, 142 146
 sensitivity to hormones, age changes, 1, 142
 transplantation of, 1, 165-166 3, 116 122-123 126
 tumours of, development, 1, 153-154
 Overwintering, 5, 232 234 240
Ovis dalli lifespan of, 5, 92-94
Ovis montanus, lifespan of, 3, 13, 14
 Oogenesis, 1, 172
 Ovulation, age of ova at time of, 1, 147-149
 in guinea pigs, 2, 71, 72, 75 83 84
 induced by gonadotrophin, 2, 75, 79, 82
 Ovis, lifespan of, 5, 99
 Oxygen, diffusion of through aortic tissue, 1, 72-74, 77
 in cell metabolism, 2, 243
 Oxygen consumption, in placenta, 2, 131-132
 Oxygen pressure, adaptation to changes, 3, 64
 Oxygen requirements of tissue, 1, 76, 77
 Palmar erythema, 1, 82
 Palometa, lifespan of, 5, 220
 Pancreas, elastase in, 1, 98, 99, 100, 3, 101-102
 mitochondria in, 2, 101
 Pancreatic juice, bicarbonate in, 4, 64
 sodium excretion in, 4, 63, 65, 71
 urea in, 4, 68-69
 Parabiosis, 1, 30, 170, 3, 116, 124, 127-128
 Paramecium, lifespan of, 3, 16
 Parasites, in fish, 5, 213-216 228
 Parentage, effect on fertility of offspring, 5, 56
 effect on lifespan, 5, 21-34, 43-47, 53, 259-262
 "Parental death", in fish, 5, 189
 Parenteral fluid therapy, 4, 144, 146-148, 151
 Parotid saliva, bicarbonate in, 4, 64
 potassium excretion in, 4, 63, 64, 65, 74, 75
 sodium excretion from, 4, 62-63, 65, 66 69, 71
 urea in, 4, 67 69 75
 Parrots, arteriosclerosis in, 5, 109, 110
 Parturition, effect of corpus luteum on, 2, 79 85
Parus major, lifespan of, 5, 100
Passer domesticus lifespan of, 5, 99
 Passeres, arteriosclerosis in, 5, 109
 Passerines, lifespan of, 5, 99-100
 Pelecaniformes, mortality rate of, 5, 101
 Pelicans, arteriosclerosis in, 5, 109
 Penguin, mortality rate of, 5, 100
 Peptic ulcers, incidence of in old people, 1, 19
Perca fluviatilis survival curves of, 5, 143, 144
 Perch, effect of diet, 5, 178
 lifespan of, 5, 220 223
 lifespan and size of, 5, 154
 survival curves of, 5, 143 144 145
 Perciformes, lifespan of, 5, 220 223 224
 Percoidae, lifespan and size of, 5, 154
 Performance, changes in with age, 3, 149-169
 experiments in study of, 3, 150-152
 in old people, 1, 42
 peak of, 1, 50-51
 problems of study of, 3, 152-153 156-159
Perognathus, lifespan of, 3, 9 10
Peromyscus lifespan of, 3, 9 10
Peromyscus leucopus lifespan of, 5, 95-96
 Personality changes, in old age, 1, 42-44
 Pharyngeal glands, in bees, 5, 233 235 237 238 239 244
 Pharynx, cancer of in old people, 1, 21

Puffer, lifespan of, 5, 221
 Pulmonary artery, calcification of elastic tissue in, 1, 98
 elastin content of, 1, 93-94
 Pulmonary oedema, 4, 284-285
Pygosteus plingstius, growth of, 5, 136, 137, 158
 Pyrogen, effects of kidney, 4, 235-238
 Pyruvate, in placenta, 2, 137
 Pyruvic acid, in urine, 4, 221
 Rabbit, adrenal cortex of, 2, 22
 cottontail, lifespan of, 5, 97
 elastin in aorta of, 1, 101
 in research on ageing, 1, 181
 lifespan of, 1, 181, 3, 11, 5, 97
 oogenesis in, 2, 36-37
 ovulation in, 1, 143
 pituitary function in foetal, 2, 20-22
 placenta of, 2, 108, 126
 renal blood content of, 3, 52, 58
 Radioiodine, deposition of in thyroid, 3, 52-58
 Radio-phosphorus, uptake of in deer antlers, 2, 177-178
 Radio-potassium, uptake of in uterus and placenta, 2, 148-160
Rajiformes, lifespan and size of, 5, 154
 lifespan of, 5, 220
Rangifer arcticus, lifespan of, 5, 92-94
Rasbora, lifespan of, 5, 224
 Rat, adrenal cortex of, 2, 22
 brown, lifespan of, 5, 95-96
 calcium metabolism in, 1, 111-114, 124-125
 causes of death in, 5, 82-83
 disease in effect on lifespan, 5, 71-89
 effect of diet on, 5, 78, 83-85, 87, 88, 251, 252, 254, 265, 268
 effect of somatotrophic hormone and cortisone on foetal growth of, 2, 161-175
 foetal, organ culture studies in reproductive tracts of, 2, 3-17
 growth in, 1, 204
 hypothermia in, 1, 168
 in research on ageing, 1, 178-180
 Kangaroo lifespan of, 5, 96
 lifespan of, 1, 177, 178-179, 180, 5, 95-96, 251, 252
 lung disease in, 5, 82
 maze experiments with, 1, 215-216
 memory in, 1, 215
 nephrosis in, 5, 83
 oestrus in, 2, 36-37
 oogenesis in, 2, 42-43
 ovarian changes in, 2, 146
 placenta of, 2, 110
 placental enzymes of, 2, 107-108
 radio-potassium uptake during pregnancy, 2, 148-160
 redundant follicles in, 2, 59-68
 response to stimuli, 3, 51, 57
 thyroid function in, 3, 52-55

Rattlesnake, fertility in, 3, 22
Rattus rattus, lifespan of, 5, 95-96
 Rays, growth of, 5, 163
 lifespan of, 5, 154, 163, 221
 size of, 5, 154
 Rectum, cancer of in old people, 1, 21
 Red cells, adenine triphosphate in, 2, 238
 ageing in, 2, 233-238
 cholinesterase activity in, 2, 235
 dissolution, 2, 218-229
 effect of cold on, 2, 224-229, 236-237, 244
 enzymes in, 2, 235, 241
 freezing of, 2, 215-216, 236-237
 haemolysis of, 2, 222, 225, 226, 227
 lifespan of, 2, 217, 233, 234, 238, 239, 241, 245
 low temperature storage of, 1, 164, 171
 membrane of, 2, 222, 223
 metabolism of, 2, 217, 227, 228, 240
 of infants, 2, 233, 239
 physical instability of, 2, 215-231
 preservation of, 2, 215
 self repair in, 2, 234
 structure of, 2, 223
 Red hind, lifespan of, 5, 220
 protein metabolism in, 5, 183-185
 Regeneration, in guppies, 5, 208-210
 Regenerative capacity of the ovary, 2, 31-58
 Regression, 1, 33-34
 Reinke, crystalloids of, 1, 92, 94, 95
 Renal artery disease, in cases of cancer, 1, 21
 Renal blood flow, 3, 193-194
 age changes in, 3, 88
 Reproduction, effect of age on in fish, 5, 181-182, 186-206
 effect of nutrition on, 1, 192
 effect of ovarian transplantation on, 1, 158, 159
 effect on lifespan, 5, 179, 275-279, 284-285
 in fish, 5, 170-174
 Reproductive organs, ageing of, tissue transplantation techniques in, 1, 141-161
 Reproductive tract, organ culture studies in, 2, 3-17
 Respiration, in barley leaves, 2, 206
 in senescent leaves, 2, 205-209, 212, 213, 214
 Respiratory acidosis, 4, 265-266
 Respiratory disease, incidence of in old people, 1, 20
 Respiratory failure, renal function in, 4, 264-270
 Respiratory function, effects of ageing on, 1, 58-68
 Retirement, effects of, 1, 49-50
 Rhinophorus, 3, 27
 Sialomucic acid, in apocrine sweat glands, 2, 194

- Polysaccharides, in elastin, 1, 104, 107
 Pompano, lifespan of, 5, 220
 Population, cross-sectional surveys, 3, 158-159, 171-172, 173-174, 179, 186
 horizontal surveys, 3, 94-95
 longitudinal surveys, 3, 95, 158, 163-164, 172-173, 174, 187
 sampling, 3, 73-79, 81, 94-96, 156-159, 171-172, 174, 183-184
 Porcupine fish, lifespan of, 5, 221
 Porgy, lifespan of, 5, 221
 Postmaturity, placenta in, 2, 112-113
 Potassium, accumulation of in cell, 4, 32-33
 activity of, in pregnant rat and goat, 2, 148-154, 159
 deficiency of, effects due to, 4, 140
 effects on kidney, 4, 262-263
 in congestive heart failure, 4, 289-292, 299-300
 deprivation of, causing cellular oedema, 4, 32
 effect of protein intake, 4, 121, 126, 129, 133
 effect on heart, 4, 95-96
 excess of, effects due to, 4, 140, 141, 144-146, 152
 in adrenal hyperplasia, 4, 80, 95
 exchangeable amounts in body, 4, 108, 109, 111, 114
 exchange of in cell, 4, 18, 19, 20, 21, 22, 24, 30, 34
 excretion of, after water loading, 4, 167-169
 effect of ACTH and cortisone, 4, 176, 177, 178
 effect of aldosterone, 4, 183-184, 186, 192-194, 196-197
 effect of cortexone, 4, 174, 175
 effect of cortisol, 4, 188, 189, 192-194, 196
 effect of cortisone, 4, 171, 172, 176, 178
 effect of vasopressin, 4, 170
 in elderly and schizophrenics, 1, 221-222, 223-236
 in parotid saliva, 4, 63, 64, 65, 74, 75
 in respiratory acidosis, 4, 266
 in sweat, 4, 63, 64, 65, 74, 76, 77
 in body of rat, 4, 120, 121, 126, 129, 133
 in erythrocytes, 4, 200-202, 204, 206, 207, 208
 in foetal urine, 4, 218
 in muscle, 4, 224-225, 289-292
 in plasma, 4, 65
 in saliva, during menstrual cycle, 4, 83-88
 loss of, 4, 226
 during labour, 4, 90
 ranges of intake, 4, 142
 Potassium chloride, effect on hyponatraemia, 4, 53
 Potassium pump, 4, 204
 Poultry, arteriosclerosis in, 5, 110, 113
 Pregnancy, aldosterone excretion in, 4, 89-90
 duration of and placenta, 2, 110, 111
 effect of corpus luteum on, 2, 78, 79, 84
 effect of cortisone on foetus, 2, 167-173
 effect of growth hormone on foetus, 2, 161-167, 171, 173-175
 effect of progesterone, 2, 126, 127
 effect on apocrine sweat glands, 2, 197-198, 199-200
 endometrial changes in, 2, 115
 placental changes in, 2, 110-111, 115
 placental uptake of radio-potassium during, 2, 148-160
 prolongation of, 2, 163
 sodium retention during, 4, 88-89
 toxæmias of, 2, 111-112, 142, 144
 uterine uptake of radio-potassium in, 2, 148-160
 water and electrolyte changes in, 4, 88-90
 water retention during, 4, 88-89
 Premenstrual oedema, 4, 81-83
 Preservation of tissue, 1, 162-172
 Procellariiformes, mortality rate of, 5, 101
 Progesterone, 1, 127, 128
 effect on placental glycogen, 2, 123, 126
 effect on pregnancy, 2, 126, 127
 Proline, in elastin, 1, 91, 94, 95, 96
 Prostate gland, cancer of in old people, 1, 21
 in female animals, 2, 14, 15, 16
 normal development of, 2, 5-6, 9, 10, 11, 14, 20
 Proteins, age changes in, 3, 66
 breakdown of, causing osmotic diuresis, 4, 41
 catabolism in senescent leaves, 2, 202-205, 206, 207-208, 212, 214
 effect of age on, 1, 103
 effect on bees, 5, 254
 effect on *Drosophila*, 5, 266-267
 in barley leaves, 2, 203-205
 in bees, 5, 234
 in cells, 3, 48, 49
 in children's diets, 1, 198
 in diet, 5, 252, 253, 254
 in elastin, 1, 94-96
 in pollen, 5, 237, 238
 in renal disease, 4, 260-262
 intake of, effect on body composition, 4, 116-138
 storage in bees, 5, 237, 238, 239
 utilization of in growth of fish, 5, 182-186, 210
 Protein metabolism, relationship with cell respiration, 2, 207-208
 Protoplasm, 1, 244
 Protozoa, nutrition and growth, 1, 186-187
 Pseudopregnancy, 3, 117, 126, 129-130
 Psittaci, arteriosclerosis in, 5, 108-109, 110
 Psychological aspects of aging, 1, 209-218
 Pudding wile, lifespan of, 5, 221

- Sodium**
 effect on water intake, 4, 37
 excess of (*see* Hypernatraemia)
 exchangeable amounts in body 4 108
 exchange of in cell, 4 18 19 20 21 22, 24 30 34
 excreted on of 4 62-63
 after water loading, 4, 167 169
 during exercise, 4, 279
 effect of aldosterone, 4 183 185 192 194 196
 effect of corticosterone 4 174 175 177
 effect of cortisol 4 187 188 189 192-194
 effect of cortisone, 4, 171 172, 173 178
 effect of vasopressin, 4 170
 in congestive heart failure 4 277 288 289 299
 in elderly and schizophrenics, 1 221 222, 223-236
 in pancreas juice, 4, 65 65 71
 in parotid saliva, 4, 62-63 65 66 69 71
 in respiratory acidosis 4 266
 in sweat, 4, 62-63 65 66 69 71 74 75 76, 77
 in tears, 4, 63 65, 71 75 76
 in body of rat, 4, 120 121 126, 132
 in erythrocytes, 4 200 201 202 203 206 207 208
 in foetal urine, 4, 217
 in plasma, 4, 65
 in saliva, during menstrual cycle 4 83-88
 in submaxillary gland 4 71 72
 loss of in adrenal hyperplasia, 4 79-80
 ranges of intake, 4, 142
 retention of in congestive heart failure, 4 288
 in pregnancy 4 88-89
 transfer of in placenta 2, 111
Sodium potassium ratios, during menstrual cycle 4 83-88
 effect of aldosterone on 4 184-185 186-187 192 194 196-197
 effect of cortisol on 4 190-192, 193-194 196
 in saliva, 4 94
Sodium pump, 4 203 207
Sole, lifespan and size of 5 150
Sorex araneus lifespan of 5 97
Souslik, lifespan of 5 97
Soya flour effect on bees 5 235
Spadefish, lifespan of 5 221
Sparrows, lifespan of 5 99
Spermatis, 2, 87 96
Spermatocytes, division of 2, 87
Spermatogenesis, 2, 86-91
 age changes in 2, 97
 condensation of karyoplasm in, 2, 90-91
 formation of acrosome and head cap, 2, 88-89
Spermatozoa, development of 2, 87 91
 low temperature storage of 1, 164 171
Sphenisciformes, mortality rate of 5, 101
Sp der naeri, 1 81 82
Sporocercosis, 3, 33 102
Sprat, lifespan and size of 5 143
Squirrel fish, lifespan of 5 220
Stallions, causes of death in 5, 68
 lifespan of 5 65-67
Starvation, effect of age 4, 266
Steady state system, 2, 216, 228
Stenor 3, 46
Sterility in cows 5, 63 64
Sterna hirundo lifespan of 5, 97 99
Steroid metabolism, changes due to age, 4 90-92
Steroids, administration of in old age, 1 134-136
 excretion of in urine, 1, 220
Sticklebacks, 3, 26
 effect of temperature on 5 168
 growth of 5 156 157 158
 lifespan of 5 152, 220 223
 size of 5 152
Stimuli, reactions to at different ages, 3 51 58
Stomach, cancer of in old people, 1, 21 24
Strength, in old age, 1 137 138
Stress, 5 88
 effect on kidney 4, 260
 recurrent, 1 12, 13 27
Strigiformes, mortality rate of 5, 101
Strix aluco lifespan of 5, 99
Sturgeon, growth of 5, 156, 157 158 163
 lifespan of 5 147 152 163 220 222, 226
 oldest age of 5, 191
 reproduction in 5 171
 size of 5, 152
 survival curves of 5 143 144
Sublingual gland, electrolytes in 4 69-70
Submaxillary gland, electrolytes in 4 69-70
Succinate dehydrogenase in placenta 2, 107 108
Sugar effect on bees, 5 256
 excretion of in elderly and schizophrenics, 1 231
Sunfish, effect of environment on 5 168
 lifespan of 5, 223
 protein metabolism of 5 182 183
Sweat, 4 100
 chlorides in 4, 64 74
 in mercury poisoning, 4 99
 potassium excretion in 4 63 64 65 74 76 77
 sodium excreted on in, 4, 62-63 65 66 69 71 74 75 76 77
 urea in, 4 67-69
Sweat glands, apocrine (*see* Apocrine sweat glands)
Swifts, lifespan of 5 100, 103 104
Synbranchiformes, lifespan and size of 5, 154

- Roach, l fspan of 5 222
 Rockfish l fspan of 5 220
 Rodents age ng in 3 9 10 11 12 13
 Rosy tetra, l fspan of 5 224
 Rubner's theory of ageing 5 125-126 128
 Rudder fish l fspan of 5 221

 Sailfish l fspan and size of 5, 154
 Saliva b carbonate in 4, 63 64 65 74 75
 83 88
 sodium n 4 62-63 65 66 69 71 83
 88
 sodium/potassium ratios in 4 94
 urea in 4 67-69 75
 Salivary glands, n bees 5, 233 235 237
 238 239
 Salmon fecundity of 5 192, 197 198
 growth of 5 156, 157 158 160-166
 l fspan of 5 150, 152 160-166 222
 mortality rates of 5 145 166
 natural death n 5, 174
 relation of size and maturity 5 172
 reproduct on in 5 179
 size of 5 150 152
Salmo gairdneri growth rates of 5 182
Salmo salar fecundity in 5 197 198
Salmonidae l fspan and size of 5 150
 l fspan and growth of 5 161 166
Sal el nus alpinus l fspan of 5 147
 Sampling 3 74 77 79 81 171 172 174
 183
 Sand dab l fspan and size of 5 148
Sardina pilchardus effect of environment
 on 5 168
 Sardines effect of environment on 5, 168
 Sauger l fspan and size of 5 154
 Scandina vians l fspan of 5 21 26
 Scar tissue collagen n 3 70
 Scat l fspan of 5, 221
 Sceloporus 3 36 27
 Schizophrenics, adrenal cortex act ty in
 3 219-238
 cort n excret on n elderly 1 221 222
 223-236
 creat n ne excret on n elderly 1 221
 222 223-236
 effect of ACTH on 1 229
 17 ketosteroid excretion in elderly 1
 221 222, 223-236
 phosphate excret on n elderly 1 221
 222 223 236
 potassium excret on n elderly 1 221
 222, 223-236
 sodium excret on n elderly 1 221 222
 223 236
 uric acid excret on n elderly 1 221
 222, 223-236
 Scombrotoxic l fspan and size of 5 154
 Sea anemone 1 244
 Sea horse, l fspan of 5 147
 l fspan and size of 5 154
 Seal oogenesis n 2 37
 Second childhood 1 34
 Seeds, age ng of 2, 211

 Seminal vesicles, normal development of
 2, 5-6 8-9 10
 Senescence, (see also Ageing)
 definition and measurement of 1 4-15
 31
 Senile death, in fish 5, 189
 Senile elastosis, 1 101 103 106-108
 Serine in elast n 1 96
 Serotonin metabolism, 3, 145, 146
 Sex differences, n body water 4, 107 110,
 113
 in growth of fish 5, 159
 in l fspan 3, 30
 in mortality among fish 5, 145 166-167
 n reactions to environment in fish 5,
 178
 Sex distribution, in emphysema, 1 68
 Sex organs, changes in due to age n fish,
 5 218
 in fish 5 229
 relationship to body weight in fish 5,
 193 196
 Sexual maturity age of 1 202 203
 and l fspan 1 29 30
 effect of diet, 5 84-85
 n fish 5 170-171
 Shad fecundity of 5 191 192
 Shark l fspan of 5 220
 Sheep, erythrocytes 4 200- 03 204 206
 in research on age ng, 1 182
 l fspan of 3 12 13 14 15 30 5, 91 94
 placenta n 2 126
 Sheephead l fspan of 5 221
 Shrews, 3 28
 l fspan of 5 97
 Siderosis, 3 107 112 188 189
Siluridae l fspan and size of 5 154
 Size effect on l fspan 5 147 159
 Skeleton, age ng of 1 109-125
 Skull effect on performance, 3, 160-161
 variations with age, 1 09 218
 Skin age changes n 1 53 3 96
 ectop flexure lines of 1 12-13
 elast c tissue n 1 100-102, 105 106
 107 108
 elast c tissue of age ng of 1 88 108
 temperature of age changes n 3 80-84
 vascular lesions of incidence of n old
 age 1 80-87
 water absorpt on by 4 100-101
 Skipjack, metabolism of 5, 170
 Smelt l fspan of 5 147
 l fspan and size of 5 150
 Snakes fertility of 3 21 22
 Snake-head l fspan of 5 2 4
 Snapper l fspan of 5 221
 Social adjustment 3 175
 Sodium, and adrenal function 4, 166
 deficiency of (see also Hyponatraemia)
 causing hyponatraemia 4 44-45
 effect of ACTH and cortisone 4 176
 177 178
 effect of protein intake on 4 121 126
 132

Urine

- output (*continued*)
 - effect of cortisol, 4, 187, 188, 192-194, 196
- pH of, 4, 209-210, 211-212, 215, 221, 222
- potassium in during menstrual cycle, 4, 84-88
- sodium in, during menstrual cycle, 4, 84-88
- steroid excretion in, 1, 220
- Lrogenital sinus, development of, 2, 20

- Valve, in elastin, 1, 91, 94, 95, 96
- Variability, 3, 71
- Vascular lesions of skin, 1, 80-87
- Vasopressin, effect on electrolytes, 4, 167, 170
 - effect on water diuresis, 4, 12, 13, 169, 170-195
- Venous lakes, 1, 85
- Venous pressure, in congestive heart failure, 4, 272, 274-275
- Venous stars, 1, 82, 86
- Ventilation, measurement of, 1, 62, 63, 66
- Vertebrates, lifespan of, 3, 9-10, 11-17
- Virus infection, in leaves, 2, 211
- Vital capacity, variations with age, 1, 58, 59-66
- Vitamin A, effect on kidney function, 4, 247
- Vitamin B, deficiency in animals, 3, 35
- Vitamin B₁₂, importance of, 1, 197, 198, 199
- Vitamin D, in calcium absorption, 1, 110, 111-114, 124
- Vitamins, effect on bees, 5, 238
 - in pollen, 5, 237-238, 239
- Vultures, arteriosclerosis in, 5, 110

Walleye, fecundity/length relationship in, 5, 197

Wasps, 5, 232, 255

- Water, cellular aspects of in body, 4, 15-35
 - content, control of, 4, 10-11
 - variations with age, 1, 207
- deficiency of causing hyponatraemia, 4, 38-44
 - effects of, 4, 140-160, 163
 - in children, 4, 160
 - symptoms, 4, 39
- deprivation of effect on hyponatraemia, 4, 31-32
- diuresis at various ages, 4, 6-10
 - effect of adrenaline, 4, 9-14
 - effect of age, 4, 238-240
 - effect of pitressin, 4, 7-8, 11
 - in congestive heart failure, 4, 272-273, 275
- effect of load in rats, 4, 167-168
- effect of vasopressin on loss of, 4, 169, 170

Water

- excess of, effects due to, 4, 46-47, 140, 141, 145-146, 150, 151
 - effect on diuresis, 4, 6, 8
 - effect on hyponatraemia, 4, 52
 - effect on urine output, 4, 4
 - in children, 4, 159
- excretion, during exercise, 4, 279
- response to adrenal steroids, 4, 180-194, 196-198
- exchanges of in body, 4, 3
- extracellular, changes in, 3, 191, 192
 - in adults, 4, 106-110
 - in children, 4, 103-106
 - variations with age, 4, 31, 110-112, 114, 115
- in body, 4, 102-115
 - effect of age on, 4, 110-112, 114, 115, 180
 - effect of growth, 4, 103-106
 - measurements of, 4, 102-103
- in muscles, 4, 113, 163-164
- in parenteral fluid therapy, 4, 146-148
- in rat body, 4, 119, 122, 123
- intake of control of, 4, 9-10
- intracellular and cardiac function, 3, 88
 - effects of age on, 4, 110-112, 114, 115
 - in adults, 4, 106-110
 - in children, 4, 103-106
- loss of, 4, 39-41, 195
 - during labour, 4, 90
 - effect of ACTH and cortisone, 4, 176, 177-178
 - effect of cortisone, 4, 174, 175
 - effect of cortisone, 4, 171, 172, 176, 178
 - following adrenalectomy, 4, 172
- metabolism, hormonal aspects of, 4, 78-98
 - in congestive heart failure, 4, 271-300
 - in infants, 4, 96-98, 154-164
 - in malnutrition, 4, 156-157
 - in pregnancy, 4, 88-90
- movement of in cell, 4, 19, 20, 22, 25, 27-29, 34
- physiological regulation of, 4, 3-14
- ranges of intake, 4, 142
- regulation of, 4, 37-38
 - by kidney, 4, 229-249
- retention of, effects of oestrogen, 4, 79
 - in congestive heart failure, 4, 288
 - in pregnancy, 4, 88-89
 - in premenstrual period, 4, 150, 151
- tolerance to excess, 4, 150, 151
- Water load, effects of, 4, 170
- Wax glands in bees, 5, 233-239
- Weakfish, lifespan of, 5, 221
- Weight, effect on lifespan, 3, 203
- Whitebait, lifespan and size of, 5, 150
- mortality rate of, 5, 146

- Tarpon, lifespan of, 5, 220
 Tears, chloride in, 4, 64, 71
 sodium excretion in, 4, 63, 65, 71, 75, 76
 urea in, 4, 67-69
 Temperature, adaptation to change, 3, 63, 64
 effect on bees, 5, 245, 246
 effect on cell, 5, 281
 effect on dissolution of red cells, 2, 218-229
 effect on lifespan, 3, 24-25; 5, 167-168
 in *Drosophila*, 5, 271-279, 283, 284
 effect on protein metabolism, 5, 185-186
 effect on senescence in plants, 2, 210
 Tench, lifespan of, 5, 223
Tenebrio molitor, effect of parental age on lifespan, 5, 262
Tentorium cerebelli, diffusion of solutes through, 1, 74-75
 Terns, lifespan of, 5, 97-99, 104
 Testis, ageing in, 2, 97
 cytomorphosis of cells in, 2, 86-99
 effect on development of reproductive tract, 2, 7-17, 19-20
 interstitial cells of, 2, 91-96
 ketosteroids in, 2, 98, 99
 Leydig cell in, 2, 91, 92, 93, 94, 95, 97, 98, 99
 of deer, 2, 179
 pituitary control by, 2, 20-21, 28
 transplantation of, 3, 123
 Testosterone, 1, 128, 129
 administration of in old age, 1, 134-136
 effect on deer antlers, 2, 179-180, 186
 effect on foetal growth, 2, 173
 Tests, mental, 1, 137
 Tests of ability and function, 1, 137
 Tetraodontiformes, lifespan of, 5, 221
 Thalamus, in old people, 1, 35-36, 49
 Thirst, effect of, 4, 143, 144
 failure of, 4, 41-43
 Thirst centre, 4, 37
 Threonine, in elastin, 1, 96
 Thrombosis, in centenarians, 1, 16
 Thunniformes, lifespan and growth of, 5, 163
 lifespan and size of, 5, 154
Thymallus signifer, 3, 26
 effect of environment on, 5, 168
 Thyroid, functions, 3, 52-55, 58
 radio-iodine uptake in, 3, 52-58
 relationship with pituitary gland, 2, 21
 transplantation of, 1, 157-158
 Thyrotrophic hormone, produced by pituitary gland, 2, 21-22
 Time, appreciation of, age differences in, 1, 217-218
 Tissue, biophysical changes during freezing, 1, 171, 172
 oxygen requirements of, 1, 76, 77
 preservation of, in study of ageing, 1, 162-172
 Tissue changes, in old age, 1, 55, 78
 in old people, 1, 27
 Tissue transplantation techniques, in the ageing of reproductive organs, 1, 141-161
 Tits, lifespan of, 5, 100
 Toadfish, lifespan of, 5, 221
 Tobacco leaves, protein in, 2, 203
 Tortoise, ageing in, 1, 28
 Totoaba, lifespan and size of, 5, 154
 Toxaemia of pregnancy, 4, 88, 89-90
 Transplantation, in inbred strains, 3, 116, 120, 122-123, 126, 129
 Trigger fish, lifespan of, 5, 221
 Triton, lifespan of, 3, 9
 Trout, effect of diet on, 5, 169, 253, 254
 effect of reproduction on, 5, 179
 fecundity in, 5, 192, 197
 food conversion in, 5, 186
 growth rates of, 5, 182
 lifespan of, 1, 29, 5, 150, 152, 222, 265
 size of, 5, 150, 152
 mortality rates of, 5, 145
 Trypsin, 3, 101
 Tryptophan, in elastin, 1, 91, 96
 Tuberculosis, in cows, 5, 63, 64
 Tuna, fecundity in, 5, 193
 lifespan and size of, 5, 154
 Turtles, in research on ageing, 1, 177
 Twins, data from, in genetics of ageing, 3, 131-148
 lifespan of, 3, 140, 141
 Tyrosine, in elastin, 1, 96
 Undernutrition, effect on children's weight, 2, 195
 Ungulates, lifespan of, 5, 91-95
 Uterus, effect of corpus luteum on, 2, 78-79
 isolated, 1, 167
 low-temperature storage of, 1, 167
 radio-potassium uptake of in pregnancy, 2, 148-160
 Urea, excretion of, 4, 40-41, 73
 in pancreatic juice, 4, 68-69
 in parotid saliva, 4, 67-69, 75
 in plasma, 4, 67
 in sweat, 4, 67-69
 in tears, 4, 67-69
 Uric acid, excretion of, in elderly and schizophrenics, 1, 221-222, 223-236
 Urinary disease, incidence of, in old people, 1, 18, 19, 20
 Urine, acids excreted in, 4, 210, 215-217, 220-222
 ammonium salts in, 4, 209-210
 calcium excretion in, 1, 120, 121, 122, 123
 cyclic changes in, 1, 236-237
 in babies, 4, 210-211
 in foetus, 4, 217
 magnesium excretion in, 4, 305, 309
 output, effect of aldosterone on, 4, 182, 192-194, 196

Wolves, lifespan of, 3, 12, 14

Wrinkling, 1, 12-13, 23, 27

X-irradiation, effect on follicular atresia,
2, 67, 68

effect on oocytes, 2, 34, 46, 49-51

Yellow tail, lifespan of, 5, 221

Yolk-sac, mitochondria in, 2, 101

2, 16

normal development of, 2, 5-6, 7-8, 10,

19

Wolfhound, lifespan of, 3, 12, 13

